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TEMPERATURE DEPENDENCE OF THERMAL DIFFUSION LENGTH FOR PLUTONIUM-BERYLLIUM NEUTRONS IN BORATED WATER

By

John Archibald Frew

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THESIS

TEMPERATURE DEPENDENCE OF THERMAL DIFFUSION LENGTH FOR PLUTONIUM-BERYLLIUM NEUTRONS IN BORATED WATER

by

John Archibald Frew

December 1970

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Temperature Dependence of Thermal Diffusion Length for Plutonium-Beryllium Neutrons in Borated Water

by

John Archibald Frew
Lieutenant Commander, United States Navy
B.S., United States Merchant Marine Academy, 1961

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

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December 1970

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ABSTRACT

The temperature dependence of diffusion length for PU-BE neutrons in distilled water poisoned with boric acid was studied using concentrations of 1.0, 8.0, 16.0, and 30.0 grams per liter. Runs at each concentration were made at temperatures of 95, 131, and 167° F. The trend of temperature dependence was clearly established. A theoretical temperature dependence of κ^2, where $\kappa = 1/L$ is proposed using a Maxwellian distribution and found to be in good agreement with the data reported in Reference [2].

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I. INTRODUCTION

The dependence of thermal neutron diffusion length upon poison concentration in water has been the subject of several experiments, the most extensive of which was done by Goddard and Johnson [2]. Using boron, a strong 1/v absorber--its cross section varies inversely with neutron velocity--these investigators carried out experiments over a wide range of boron concentrations.

The object of this study was to determine diffusion length as a function of boron concentration and temperature. An attempt was made to represent both the absorption and the temperature dependence of diffusion length in a polynomial approximation. This experiment was conducted using a plutonium-beryllium source.

II. THEORY

A. ONE GROUP THERMAL NEUTRON DIFFUSION

For a point source of thermal neutrons in an infinite hydrogeneous medium, the one group thermal diffusion equation may be written in spherical coordinates as

$$\frac{1}{r^2} \frac{d}{dr} \left(r^2 \frac{d\,\Phi_T}{dr} \right) - \frac{1}{L^2} \Phi_T = 0 \qquad (1)$$

Using the source condition

$$\lim_{r \to} r^2 \; J\,(r) = \frac{S}{4\pi}$$

where,

$$J = -D \frac{d\Phi}{dr}$$

the solution to the diffusion equation is,

$$\Phi_T = \frac{Se^{-r/L}}{4\pi Dr} \qquad (2)$$

Where S is the source strength in neutrons/sec.

The determination of the diffusion length would now be possible using the above solution if the neutron source were, in fact, thermal. However, the PU-BE neutron source emits neutrons with an average kinetic energy of approximately 4.2 MEV. The actual neutron spectrum extends from very low energies to about 10.6 MEV. In order to use the one group thermal model, it is necessary to account for the PU-BE neutron energy spectrum. This is accomplished

by considering the neutrons as being born in two groups; a fast group with an energy range above .025 ev up to 10.6 MEV and a thermal group with energy .025 ev. The next simplifying assumption is to assume all the neutrons born to the fast group are born at the average group energy. The actual energy distribution is shown in Figure 1, hence there would be many different migration areas [6]. It is assumed that the fast neutrons are born at an average energy and therefore, there will be an average migration area. The average energy of the PU-BE neutrons is 4.2 MEV.

Now having lumped the fast neutrons into a single energy group, the source term in the diffision equation can be derived. This term must represent those source neutrons that are born fast and have slowed down to thermal energy. The one group diffusion equation written with the source term has the following form:

$$\frac{1}{r^2} \frac{d}{dr} r^2 \frac{d \Phi_T}{dr} - \frac{1}{L^2} \Phi_T + \frac{S(r)}{D} = 0 \qquad (2A)$$

B. SOURCE TERM DEVELOPMENT

For an isotropic point source in an infinite medium, the source releases S_o neutrons per unit time. Since in hydrogeneous media a fast neutron may loose all energy after one collision, the density of first scattering collisions is given by [5].

$$q\ (r, E_{TH}) = \frac{S_0}{4\pi r^2} \Sigma_s(E_0) e^{-\Sigma_s(E_0)} \qquad (3)$$

For an infinite hydrogen medium, the slowing down density at any energy is constant and equal to the source density [4]

$$S(r) = q\ (r,E) \tag{4}$$

Therefore, for a point source emitting fast neutrons at E_o, the number of neutrons entering the thermal region is given by

$$S(r) = q\ (r,\ E_{TH}) = \frac{S_o\ \Sigma_s\ (E_o)\ e^{-\Sigma_s(E_o)r}}{4\pi r^2} .$$

substituting into equation (2A) results in

$$\frac{1}{r^2}\ \frac{d}{dr}\ \frac{r^2 d\Phi_T}{dr} - \frac{1}{L^2}\ \Phi_T + \frac{S_o\quad (E_o)e^{-\Sigma_s(E_o)r}}{4\pi D r^2} = 0 \tag{6}$$

or

$$\frac{1}{r^2}\ \frac{d}{dr}\left(r^2\ \frac{d\Phi_T}{dr}\right) - \frac{1}{L^2}\Phi_T + C\ \frac{e^{-r/b}}{r^2} = 0 \tag{7}$$

where,

$$C = \frac{S_o \Sigma(E_o)}{4\pi D} \qquad \text{and} \qquad 1/b = \Sigma_s(E_o)$$

C. SOLUTION OF DIFFUSION EQUATION

In the development a first collision density is assumed and Σ_s is assumed constant at the average energy of the fast neutron. The homogeneous solution to this equation is:

$$\Phi_H = A\ \frac{e^{-r/L}}{r} + B\ \frac{e^{+r/L}}{r} \tag{8}$$

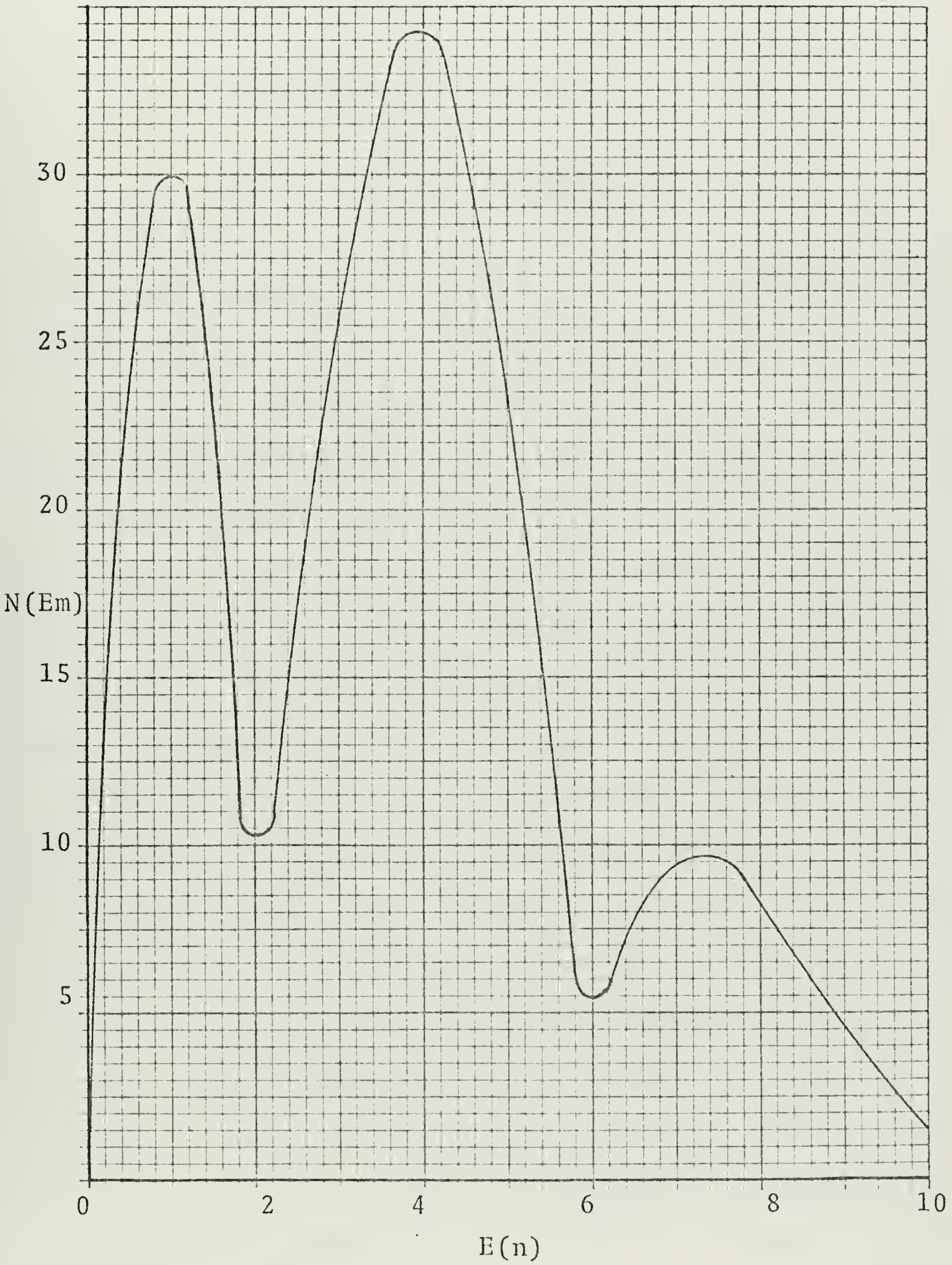


FIGURE 1. Neutron Spectrum for a PU-BE Source.

Since the flux must be finite everywhere, B must be zero. Assuming a particular solution of

$$\Phi_P = E \frac{e^{-r/b}}{r^2} \tag{9}$$

and substituting in Equation (7) yields

$$\Phi_T = \Phi_H + \Phi_P$$

$$\Phi_T = A \frac{e^{-r/L}}{r} - \frac{Cb^2L^2e^{-r/b}}{Dr^2(L^2-b^2)} \tag{10}$$

This is the asymptotic solution (i.e., the solution for $r \to \infty$) for Equation (6).

If L^2 is larger than b, the first term of Equation (10) becomes much more significant than the second term at some sufficiently large r and the flux can be assumed to decay as a simple exponential. For PU-BE sources b is larger than L^2, hence the complete expression must be retained to correctly describe the neutron diffusion. The several unknows associated with this equation; namely, the constant A, the parameters D,b considerably increase the difficulty of determining an accurate diffusion length. Even though it has been possible to develop a theoretical expression for flux based on a one group model with a source term to account for the fast neutrons, this expression is not simple and does not lend itself to a straightforward determination of diffusion length. However, it is still possible to proceed by turning to the relationship between diffusion length, age, and migration

area. Although this method is far from simple it does offer a solution. The next step will be to develop the expression for age and migration area.

D. NEUTRON AGE CALCULATION

The definition of age can be derived from the reactor criticality equation written in the moment form [6]

$$\frac{K_\infty}{1+L^2B^2} \sum_{n=0}^{\infty} \frac{(-1)^n B^{2n} \overline{r^{2n}}}{(2n+1)!} = 1 \qquad (12)$$

For an infinite medium it is possible to neglect all terms greater than n = 1. The summation of equation (12) can be written as:

$$1 - \frac{B^2\overline{r^2}}{3!} + \frac{B^4\overline{r^4}}{5!} + \frac{B^6\overline{r^6}}{7!} + \cdots$$

Now setting the above approximation equal to the critically equation in the form

$$\frac{K_\infty e^{-B^2\tau}}{1+ L^2B^2} = 1 \qquad (13)$$

we get

$$e^{-B^2\tau} = 1 - \frac{B^2\overline{r^2}}{3!}$$

when all terms in the series with n>1 has been neglected. Using a series expansion of the exponential, the expression becomes

$$1 - B^2\tau = 1 - \frac{B^2\overline{r^2}}{3!} \qquad (14)$$

which yields:

$$(E_o,E) = \frac{\overline{r^2}\ (E_o,E)}{6} \qquad (15)$$

The age relates to the mean-square distance traveled by a neutron from its point of birth as a fast meutron to the point at which it becomes thermal.

The mean-square (net vector) distance, $\overline{r^2}$, which a neutron travels from its source to where it is absorbed, is given by [3].

$$\overline{r^2} = \frac{\int_0^{\infty} r^2 \quad 4\pi r^2 \Sigma_a \Phi \ dr}{\int_0^{\infty} 4\pi r^2 \ \Sigma_a \ \Phi \ dr} \qquad (16)$$

Substituting

$$\Phi(r,E) = \frac{q \ (r,E)}{\xi \ E \ \Sigma_s} \qquad (17)$$

from the age-diffusion theory, gives

$$\overline{r^2} = \frac{\int r^2 q \ (r,E) \ dV}{\int q \ (r,E) \ dV} \qquad (18)$$

The saturated activity can be written as

$$A_s \simeq V \ \Sigma_a \ \Phi \qquad (19)$$

where both the macroscopic cross-section and the flux are functions of energy. Integrating over the energy range of interest and substituting Equation (17) into Equation (19) yields:

$$A_s = V \quad \frac{q\ (E)\ \Sigma_a(E)}{\xi\ \Sigma_s} \quad \frac{dE}{E} \tag{20}$$

For the single resonance peak of indium it is possible to assume: (1) the integral is small except at the resonance peak, (2) the slowing-down density is independent of energy and (3) the moderating power ($\xi\Sigma_s$) is constant over the peak. Equation (20) may now be written as

$$A_s = \frac{qV}{\xi\Sigma_s} \qquad \Sigma_a(E) \ \frac{dE}{E} \tag{21}$$

This shows that the slowing down density is directly proportional to the saturated activity. Substituting Equation (2) into Equation (18) yields:

$$\overline{r}_s^{\,2} = \frac{r^2\ A_s\ (r)\ dr}{A_s\ (r)\ dr} \tag{22}$$

which for cadium-covered foils becomes

$$r^2_{CD} = \frac{\int_0^\infty r^4\ A_{CD}\ (r)\ dr}{\int_0^\infty r^2\ A_{CD}\ (r)\ dr} \tag{23}$$

Finally,

$$\tau_{IN} = \frac{\overline{r^2}_{CD}}{6} = \frac{1}{6} \frac{\int_0^\infty r^4\ A_{CD}\ (r)\ dr}{\int_0^\infty r^2\ A_{CD}\ (r)\ dr} \tag{24}$$

An experimental evaluation of Equation (24) is included in Appendix B.

E. DETERMINATION OF MIGRATION AREA

The total mean-square distance a neutron travels from its point of birth to its point of interaction, ${r^2}_t$, consists of two parts: (1) the mean-square distance covered in slowing down process, ${r^2}_s$ and (2) the mean-square distance covered in the process of thermal diffusion, ${r^2}_{th}$. The first parameter correlates with the age, and the second parameter correlates with thermal diffusion length, L^2 [6]. The migration area is defined as

$$M^2 = \tau + L^2 \tag{25}$$

The correlation between ${r_t}^2$ and M^2 is given by

$$M^2 = \frac{\overline{r}_t^{\,2}}{6} = \frac{\int_0^\infty r^4 \; A_s(r)\, dr}{\int_0^\infty r^2 \; A_s(r)\, dr} \tag{26}$$

The integrals can be obtained in a manner analogous to the derivation of Equation (24) for ${r_s}^2$.

F. TEMPERATURE DEPENDENCE APPROXIMATIONS

In order to formulate the temperature dependence of diffusion length a series expansion in absorption cross section Σ_{ao} of the form suggested by reference [2] was utilized.

$$K^2 = \alpha_0 + \alpha_1 \Sigma_{ao} - \alpha_2 \Sigma^2_{ao} + \alpha_3 \Sigma^3_{ao} \tag{27}$$

where K is the inverse of the diffusion length, Σ_{ao}, is the sum of the 2200m/sec macroscopic absorption cross sections for boron and hydrogen and the α's are coefficients to be determined. We shall attempt to include the temperature dependence in the expansion defined by Equation (29).

A first approximation of temperature dependence was derived by assuming a Maxwellian distribution [4] for neutron flux.

$$\Phi_n(E) = \frac{2\pi n}{(\pi kT)}^{3/2} \left(\frac{2}{m}\right)^{\frac{1}{2}} E\, e^{-E/KT} \tag{28}$$

where n is the density of neutrons, K is Boltzmann's constant, m is the meutron mass, and T is the temperature of the medium in degrees Kelvin. By setting the derivative of Equation (28) equal to zero it can be shown that the most probably velocity is given by [4]

$$V_T = 1.284\ T^{\frac{1}{2}} \times 10^4\ {}^{cm}/_{sec} \tag{29}$$

from this

$$\frac{V_T}{V_o} = \left(\frac{T}{T_o}\right)^{\frac{1}{2}} \tag{30}$$

where V_o is the most probable velocity for a Maxwellian flux at 293.6°K.

Using this relationship it is possible to relate the average thermal macroscopic cross section as a function of temperature [4].

$$\Sigma_a = \frac{\sqrt{\pi}}{2} \left(\frac{T_o}{T} \right)^{\frac{1}{2}} \Sigma_a(E_o) \qquad (31)$$

This relationship was applied to the polynomial approximation with the temperature dependence being applied to the coefficients. In order to test the validity of the approximation the data reported by reference [2] at 22.3°C was used for the initial data at T_o. This approximation was found to correlate very well with the data at 65°C from the same reference. The relatively large error associated with the present research precludes any conclusion more specific than that trend of the data is in the direction of the approximation. Figure (7) is a plot of K^2 versus Σ_a for various temperatures using the temperature dependent approximating polynomial.

III. DESCRIPTION OF THE EXPERIMENT

Indium foil activation measurements were made in heated water poisoned with boric acid (H_3BO_3). Fifteen indium foils were placed in a plexiglass holder at intervals of 1/2 inch. The holder was located in the center of a 22 X 30 X 23 inch tank made of 1 inch plexiglass. The tank contained approximately 45 gals. of distilled water. Two, rheostat controlled, 500KW emersion heaters were used to heat the tank. Temperature control within 1/2°F was provided by a Thermistemp unit controlling a third emersion heater rated at 750KW. The tank was kept at a uniform temperature by a variable speed electric stirrer.

The tank was located on top of a second tank containing the radioactive PU-BE source. This steel tank was 2.95 feet in diameter, 1.25 high and contained 65 gals. of water. The sources were contained in three stainless steel tubes arranged in a triangular configuration. The highest source was located 5/8 inches from the top of the tank. The sources were located directly under the foil column by three plexiglass extension rods.

The three source strengths were 1, 1, and 3 curies. Since the sources were anisotropic, the extension rods were marked so that the sources could be placed to insure the same exposure during every run. Figure 2 shows the experimental set-up.

Saturated boric acid solutions were added for poisoned runs. After thorough mixing, samples were drawn and analyzed checmically as described in Appendix A.

Fifteen foils were used for each run. The relative flux was measured with bare indium foils 1.0 inches in diameter and .01 inches thick. Indium resonance activity was measured with similar foils placed in cadmium covers .020 inches thick. Irradiation time for each run was three hours. The foils were removed, one at a time, and allowed to decay for three minutes before counting. This waiting time allowed the 13 second half-life In^{116} to decay to a level that would not interfere with the 54 minute activity. Foils were counted for three minutes using the equipment specified in Table I. This counting technique resulted in standard deviations ranging from .1 to 10 percent. Background counts were taken before and after each run and averaged. The average background was subtracted from the foil counts before correction factors were applied.

Detector		GM tube
operating voltage		1300 volts
Voltage Supply	Hewlett-Packard	Model 6516A
Preamplifier	Hewlett-Packard	Model 1045A
Time-Scalar	Hewlett-Packard	Model 5201L

TABLE I.

COUNTING EQUIPMENT

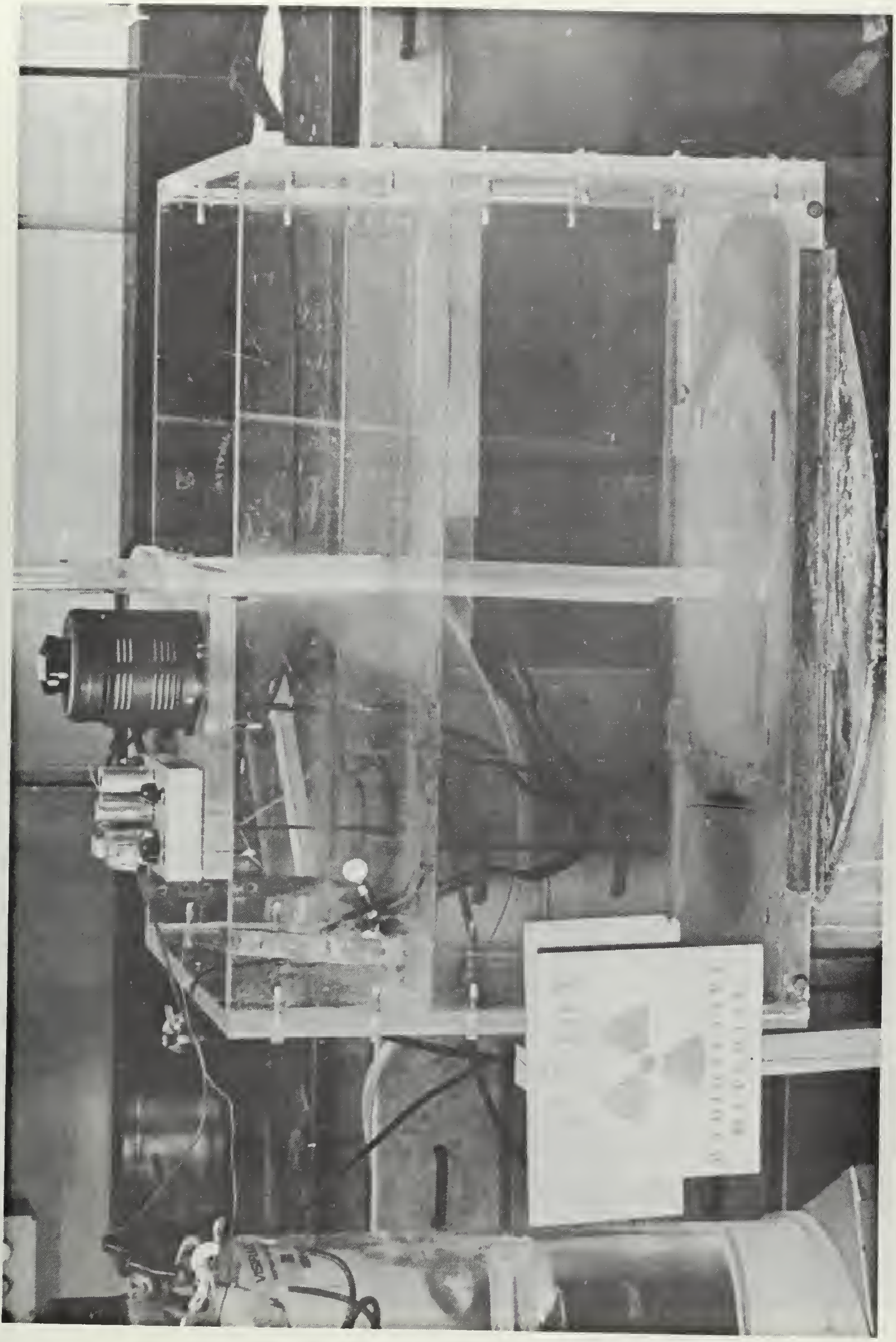


FIGURE 2

EXPERIMENTAL APPARATUS

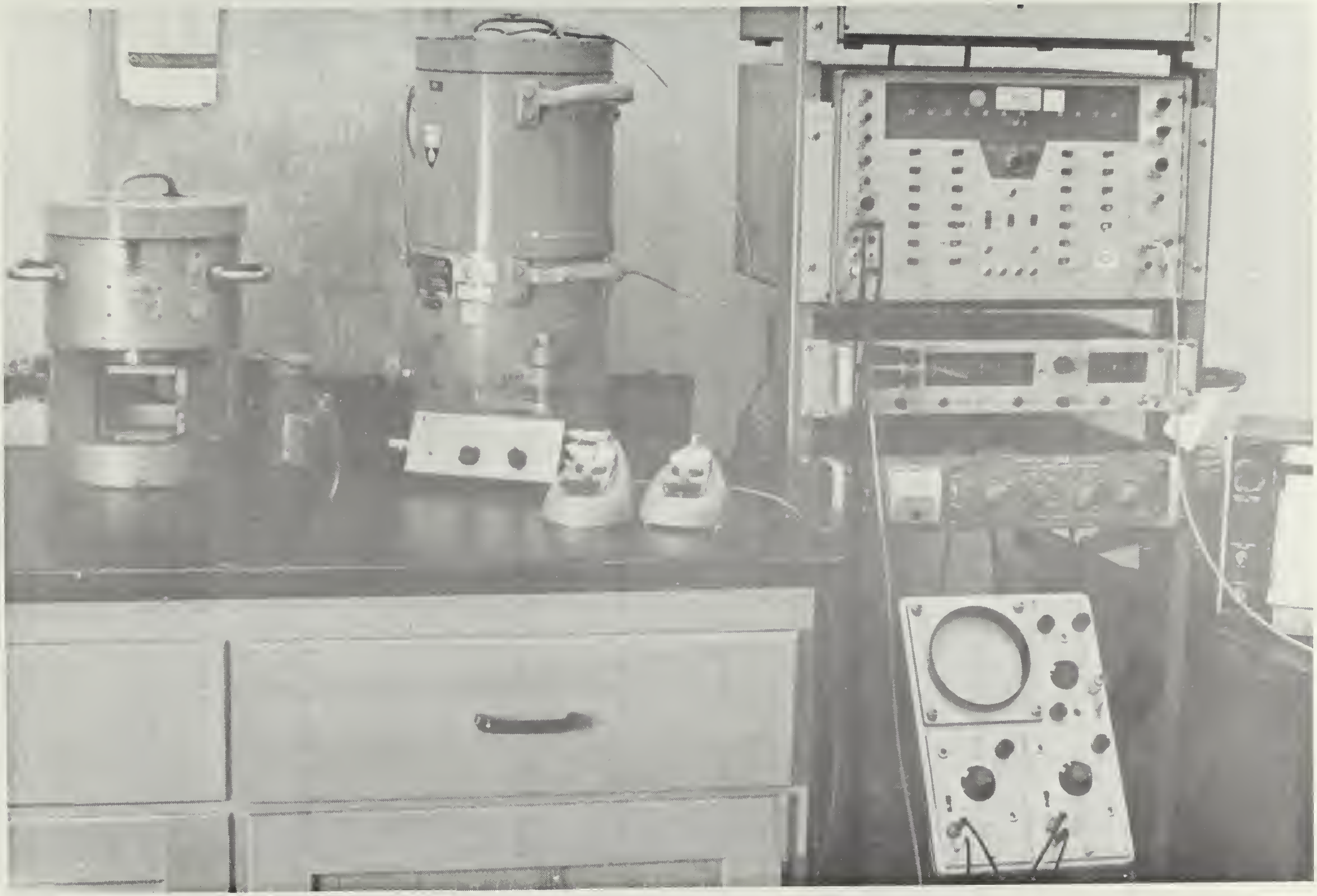


FIGURE 3. COUNTING EQUIPMENT

IV. ANALYSIS OF DATA

A. ACTIVATION DATA

Each run was conducted with fifteen foils. The foils were irradiated for three hours, removed one at a time, then counted-starting with the foil closest to the source. In this way, the foils with the lowest counts were irradiated as long as possible to improve the counting statistics. Foil counts were corrected for differences in foil weights, absorption of indium resonance neutrons by the cadmium and counter resolving time.

Foil weights were normalized to 1.0 gram. Correction factors ranged from 1.071 to 1.082.

The indium resonance counting rate correction was 1.11 as determined from reference [10].

Counter resolving times were determined by the two-source method using

$$\frac{A_1}{1-N_1 t} = \frac{A_2}{1-N_2 t}$$

where A is the saturated activity, N is the mean counting rate, and t is the resolving time. A correction factor of $1/(1-N_t)$ was applied to all counting times.

The saturated activity was calculated using the corrected counts in the equation

$$A_s = \frac{\lambda C}{(1-e^{-\lambda t_1})\, e^{-\lambda(t_2 - t_1)}\, (1 - e^{-\lambda(t_3 - t_2)})}$$

where,

t_1 - irradiation time
t_2 - time counting started
t_3 - time counting stopped
$t_2 - t_1$ - waiting time
$t_3 - t_2$ - counting time

Having calculated the relative saturated activity, the quantities Asr^2, Asr^4, $A_{cd}r^2$ and $A_{cd}r^4$ were computed and plotted versus the distance from the source. The computer program used for these calculations is described in Appendix D.

B. RELAXATION LENGTH

Equation (6) gives the space dependence of the slowing-down density as

$$q\ (r,E) = \frac{C\ e^{-r/b}}{r^2} .$$

Since the activity is proportional to the slowing down density as shown in Equation (21), we have

$$A_s = \frac{C\ \ e^{-r/b}}{r^2} \tag{32}$$

Rewriting and taking the logarithum of both sides yields

$$\ln A_s r^2 = \text{CONST} - r/b \tag{33}$$

The quantity $\ln A_s r^2$ was plotted against distance. The relaxation length is the negative reciprocal of the slope.

The same method was used to determine the relaxation length associated with the indium resonance activity.

C. AGE AND MIGRATION AREA

Equations (24) and (26) were used to determine Age and Migration Area. Computer Program No. 1 (Appendix D) plotted graphs of Asr^2, $A_{cd}r^2$, Asr^4, and $A_{cd}r^4$ versus r. A smooth curve was drawn through the data points up to a radius of 12 cm. At 12 cm the plot was considered exponential and extrapolated to infinity by means of a curve formed from the equation

$$Asr^2 = C\ e^{-r/b}$$

where b is the relaxation length, determined from curve fitting of measured activities and the logarithmic plot. The areas under the Asr^2 and $A_{cd}r^2$ curves were determined by Simpsons rule. The areas for Asr^4 and $A_{cd}r^4$ were determined by multiplying the Ar^2 data points by r^2 and integrating the result, rather than integrating the Asr^4 and $A_{cd}r^4$ curves directly. After the areas had been computed the second moments were determined by Equations (23) and (26); and finally Age and Migration Area were found from Equations (24) and (26). The computer program used for these computations is Appendix E. Plots of Asr^2 and $A_{cd}r^2$ are included in Appendix B.

D. DIFFUSION LENGTH

Diffusion length is determined from Equation (11). The Age that has been determined is to the indium resonance.

1.8 cm^2 was added to the Age to account for the Age increase from indium resonance to thermal energies [6]. The nature of the calculation-the difference of two relatively large numbers-leads to considerable variation in the results even under the best experimental conditions. Small errors (±.5 cm^2) in the computed values of the Migration Area and Age lead to 20 percent change in the value of diffusion length. If errors are estimated to be 2.5 cm^2, a very reasonable estimate for this experiment, the value of diffusion length at higher poison concentrations will vary 200 percent. As the poison concentration is increased, diffusion length decreases and using the same estimates of error the percent error becomes very large. From this it is concluded that the results of this experiment serve only to show the trend of the temperature dependence of diffusion length and the values determined should not be considered absolute.

TABLE II

TEMPERATURE 95°F

Boric Acid g/l Concentration	Age	Migration Area	Diffusion Length
8 ± .5	58.5 ± 2.1	62.5 ± 1.9	1.5 + .6 - 1.3
16 ± .6	58.6 ± 1.8	61.6 ± 2.0	1.1 + .9 - 1.1
30 ± 1.1	58.4 ± 1.9	60.9 ± 2.2	.9 + 1.9 - .9

TABLE III

TEMPERATURE 131°F

Boric Acid g/l Concentration	Age	Migration Area	Diffusion Length
8 ± .5	59.5 ± 1.8	63.6 ± 1.7	1.5 + .7 - 1.5
16 ± .6	59.6 ± 1.9	60.9 ± 1.8	1.2 + .6 - 1.2
30 ± 1.1	59.6 ± 2.0	62.2 ± 2.2	.9 + 1.1 - .9

TABLE IV

TEMPERATURE 167°F

Boric Acid g/l Concentration	Age	Migration Area	Diffusion Length
8 ± .5	60.2 ± 1.7	64.4 ± 2.1	1.6 + .8 - 1.6
16 ± .6	60.4 ± 1.7	63.1 ± 2.0	1.2 + .6 - 1.2
30 ± 1.1	62.9 ± 1.9	60.3 ± 2.2	.9 + 1.0 - .9

M_T^2 and τ_{IN} versus POISON CONCENTRATION AT 95°F

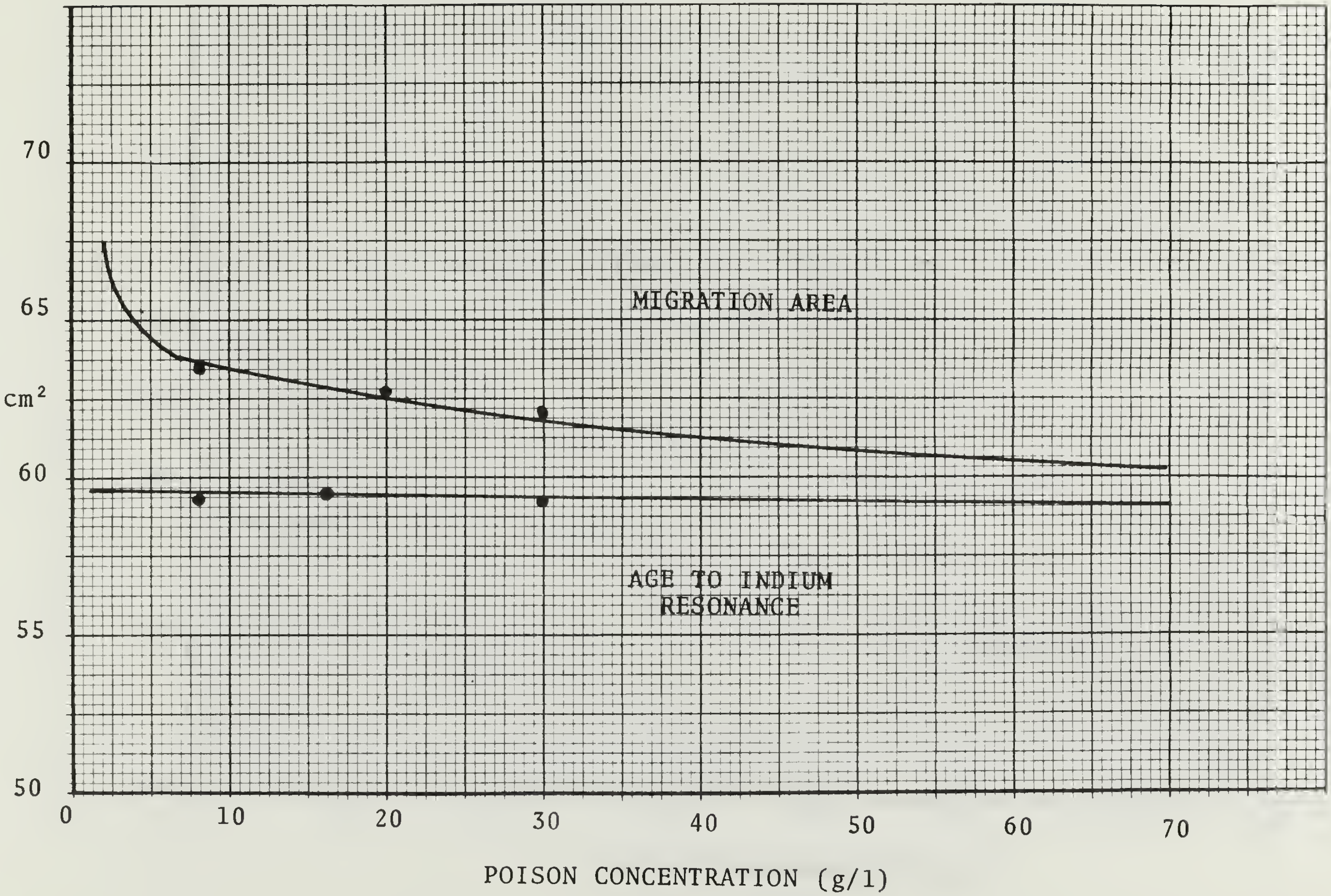
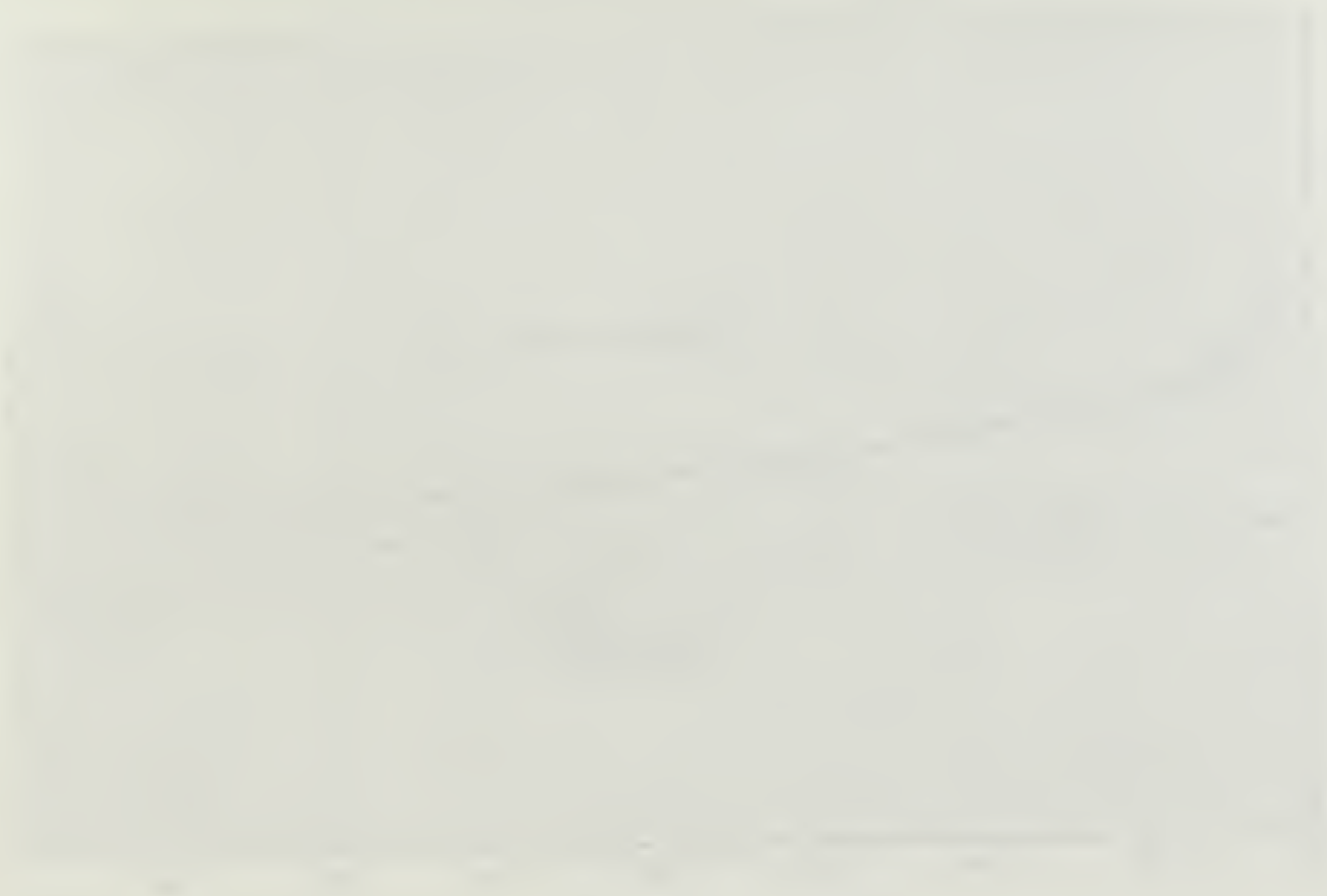


FIGURE 4

[illegible]



$M_T{}^2$ and τ_{IN} versus POISON CONCENTRATION AT 131°F

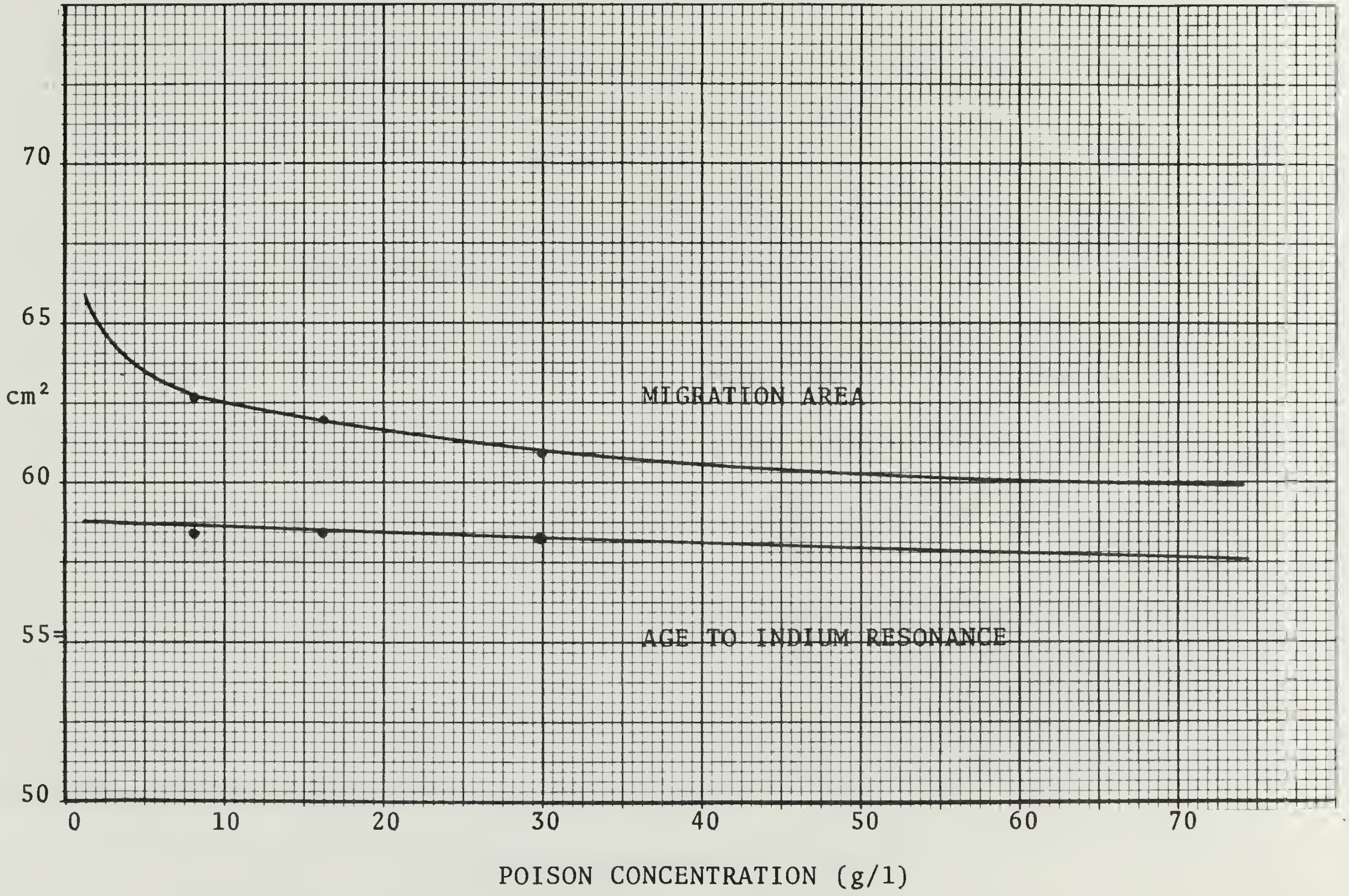


FIGURE 5

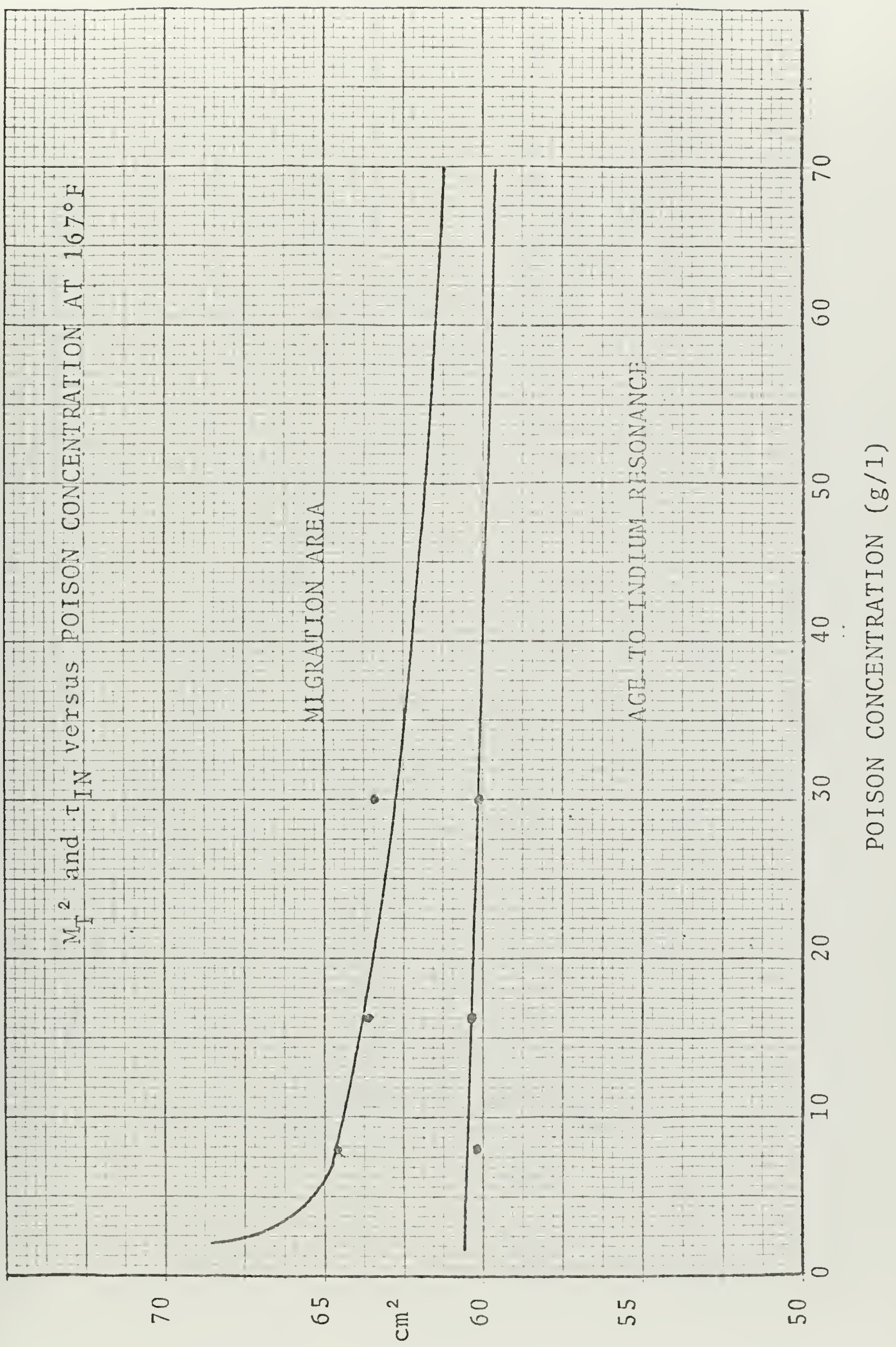

M_T^2 and τ_{IN} versus POISON CONCENTRATION AT 167°F

FIGURE 6

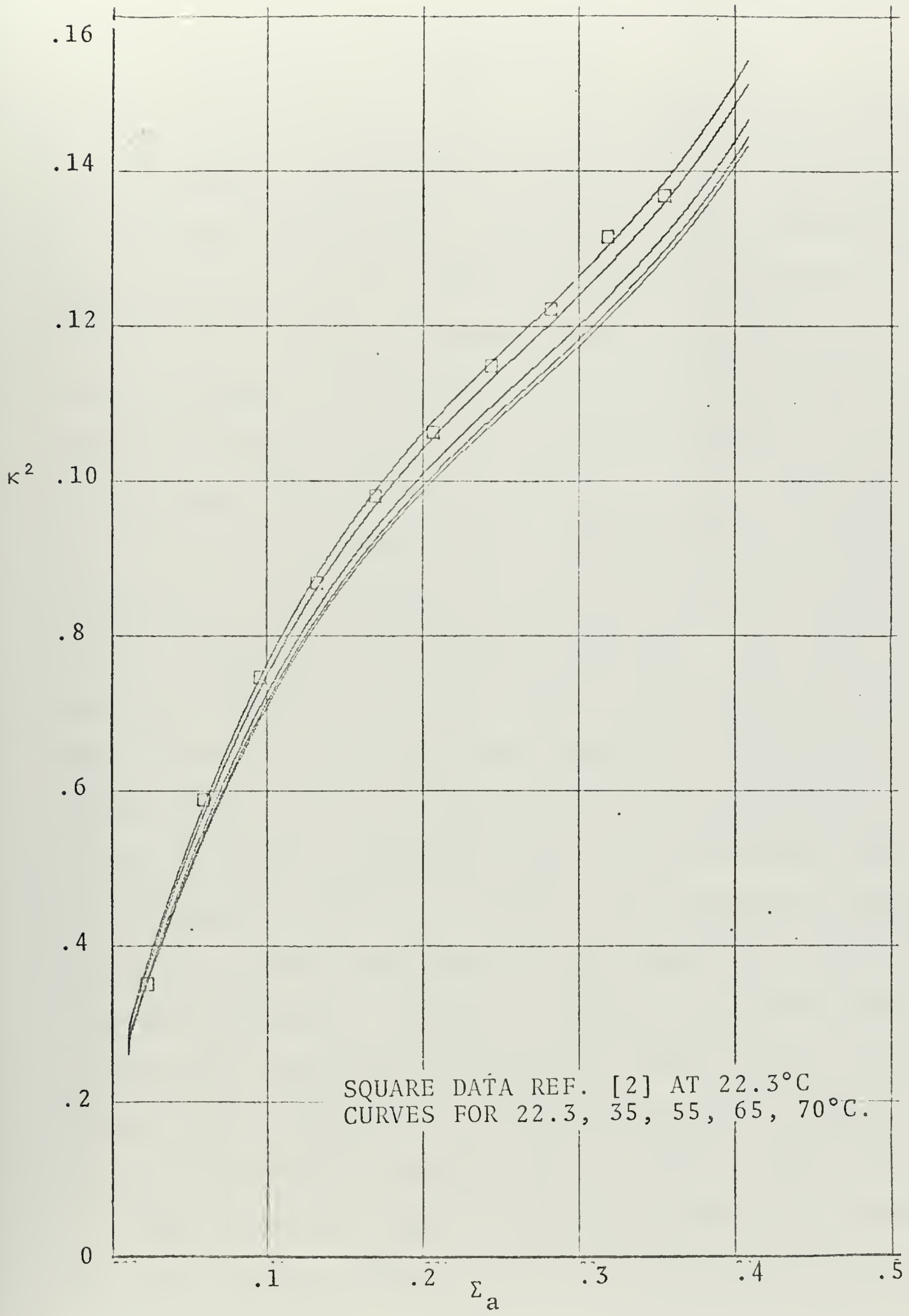
.16
.14
.12
κ^2 .10
.8
.6
.4
.2
0
.1
.2
.3
.4
.5
Σ_a
SQUARE DATA REF. [2] AT 22.3°C
CURVES FOR 22.3, 35, 55, 65, 70°C.

FIGURE 7

V. CONCLUSIONS

Both Age and Migration Area were found to be relatively weak temperature dependent parameters in the temperature range under investigation. The trend of the temperature dependence was clearly established and in agreement with the theory. Errors associated with the calculations of these parameters were mainly due to the statistical errors from the weak neutron sources and the location of the neutron origin. The products $A_s r^2$, $A_s r^4$, $A_{cd} r^2$, and $A_{cd} r^4$ were greatly influenced by the position of the origin. The triangular configuration of the sources made the selection of one origin for all neutrons difficult. The first origin selected was the geometric center of the three sources. The validity of this reference point was tested by comparing the relaxation lengths obtained for pure water with those reported in references [6, 9]. The results were not in agreement. The best agreement was obtained by assuming an origin on the top surface of the uppermost (also the strongest) source. However, it should be pointed out that this forces the assumption that all neutrons are born at this point when actually the neutrons from the other source are born at a significantly different distance.

The diffusion length in this experiment was determined by computing the square root of the difference between Age and Migration Area. Because of the nature of the calculation the relatively small uncertainties associated with

these parameters can and did lead to very large uncertainties in the diffusion length. The investigator is hesitant to place too much weight on the final values of diffusion length. Rather than draw any conclusions as to exact values of diffusion length the results are reported only to show the trend of the temperature dependence of diffusion length.

Using a polynomial expansion suggested by Ref [2] a successful effort was made in representing both the temperature and the absorption dependence of diffusion length. The form of the temperature dependence was derived from the Maxwellian distribution and applied to the macroscopic absorption cross section. The plots of the approximation were in excellent agreement with the data reported in reference []]. It is hoped that this approach will serve as a basis for further work in this area and that the approach will prove successful at higher temperatures and poison concentration.

APPENDIX A: DETERMINATION OF BORIC ACID CONCENTRATION

A. 1 gram of Boric Acid (H_3BO_3) was dissolved in 300 ml of distilled H_2O. Twenty-five ml of glycerol and 10 drops of phenophthlen indicator were then added and the resulting solution was titrated using a .1N NaOH solution. A distinct reddish-pink color marked the titration end-point. This titration established the molarity of the standard.

B. Sample Analysis

A 25 ml sample was drawn for analysis. To this sample were added 5ml of glycerol and 4 drops of phenophthalein. This sample was then titrated using a .1N NaOH solution.

C. Sample Calculation

143 ml of standard (.1N) NaOH solution was used to reach end-point of the standard solution (1 gm dissolved in 300 ml H_2O). 27.5 ml of NaOH produced end-point in sample.

$$\frac{27.5 \text{ ml}}{25 \text{ ml}} \text{ (SAMPLE)} = \frac{y \text{ ml}}{300 \text{ ml}} \text{ (STANDARD)}$$

$$y = 33 \text{ ml}$$

From standard

$$\frac{1 \text{ gm}}{300 \text{ ml}} = 3.33 \text{ gm/liter}$$

$$\frac{143 \text{ ml}}{3.33 \text{ g/l}} = \frac{33\text{ml}}{x}$$

$$x = 7.7 \text{ gm/liter}$$

APPENDIX B

LOTS OF $A_s r^2$ and $A_{cd} r^2$ FOR POISON RUNS

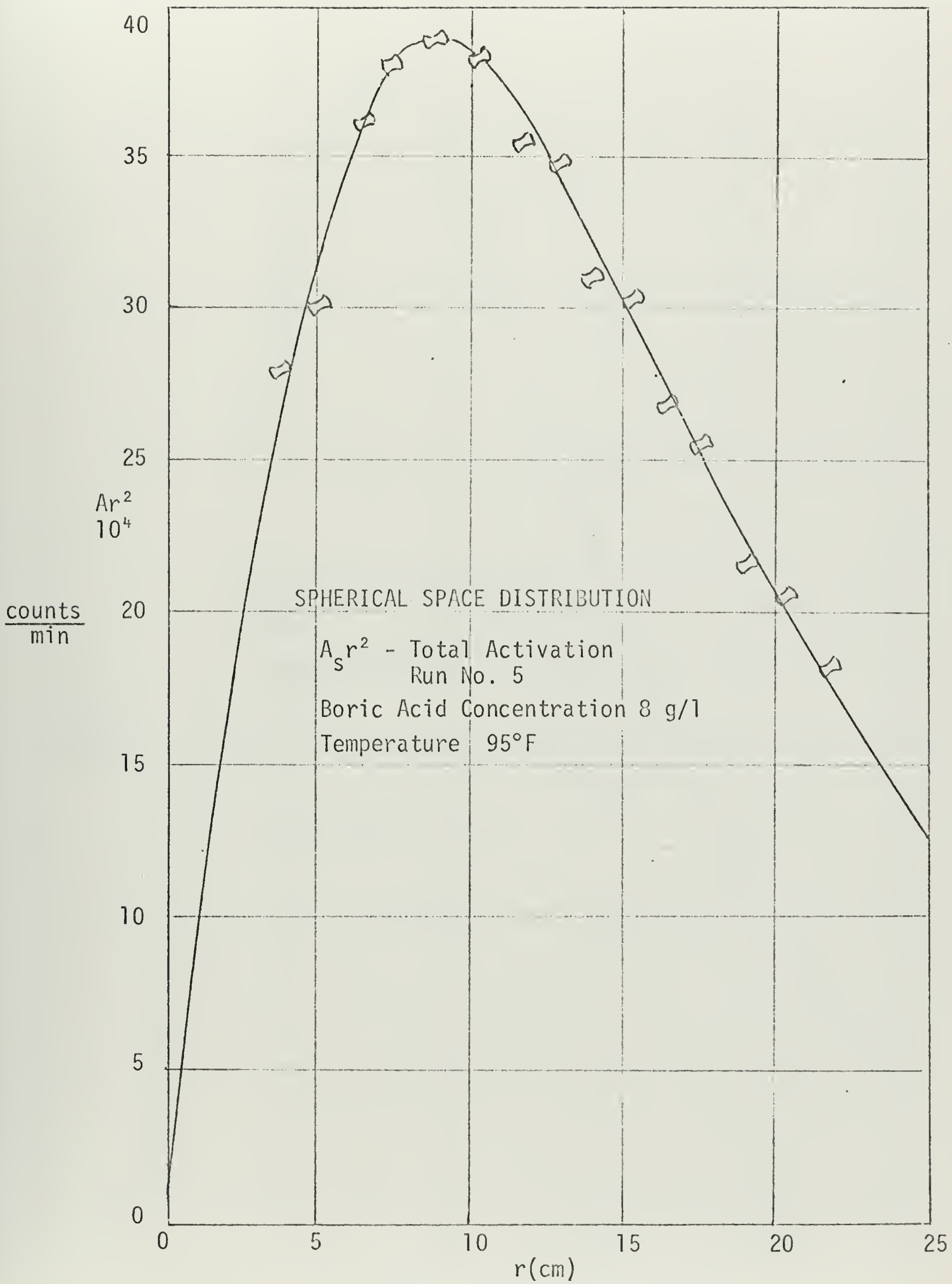

40
35
30
25
20
15
10
5
0
$\frac{Ar^2}{10^4}$
$\frac{\text{counts}}{\text{min}}$
0
5
10
15
20
25
r(cm)
SPHERICAL SPACE DISTRIBUTION
$A_s r^2$ - Total Activation
Run No. 5
Boric Acid Concentration 8 g/l
Temperature 95°F

FIGURE 9

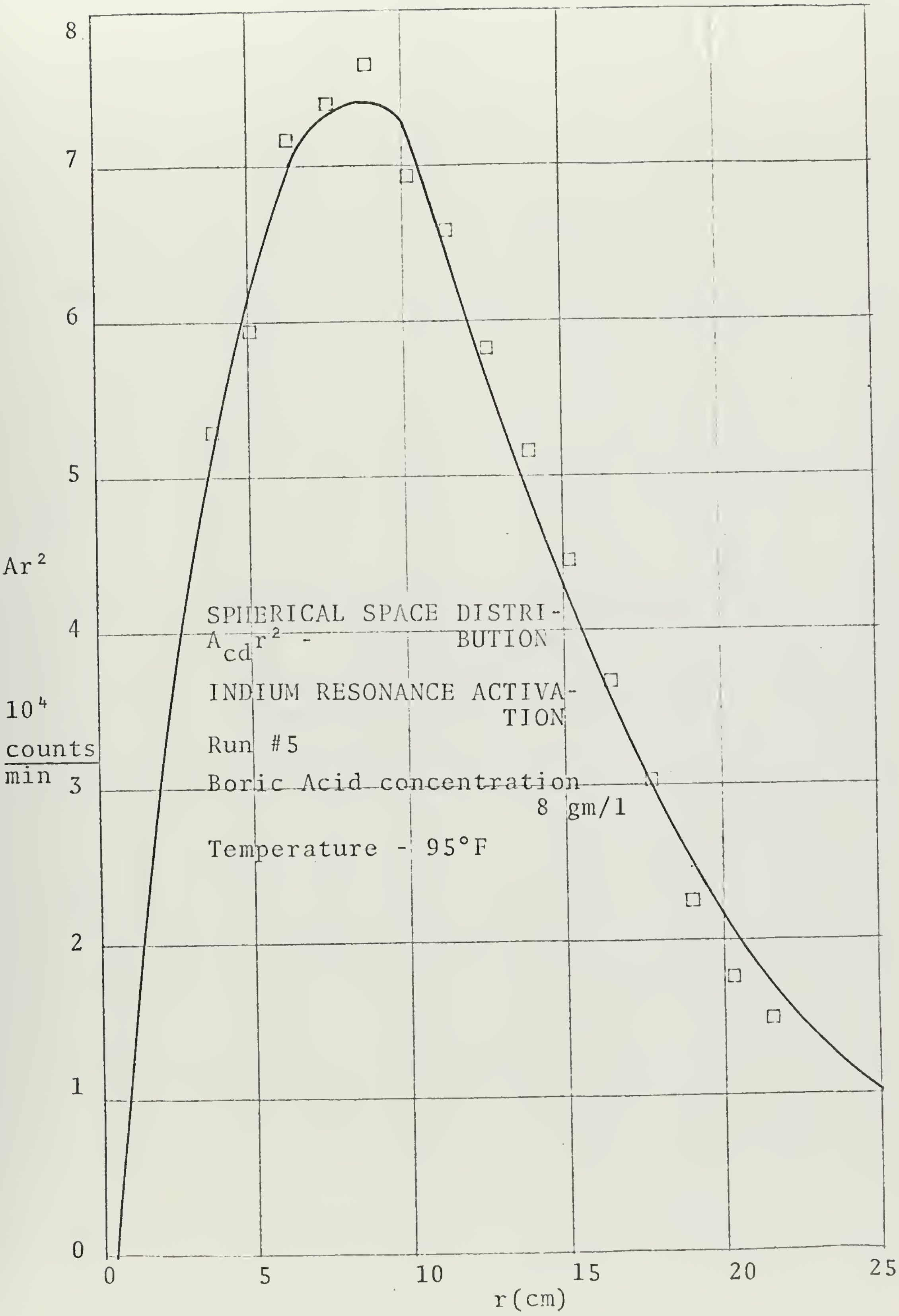
8
7
6
5
4
3
2
1
0
Ar²
10⁴
counts/min
0
5
10
15
20
25
r(cm)
SPHERICAL SPACE DISTRIBUTION
$A_{cd}r^2$ -
INDIUM RESONANCE ACTIVATION
Run #5
Boric Acid concentration 8 gm/l
Temperature - 95°F

FIGURE 10

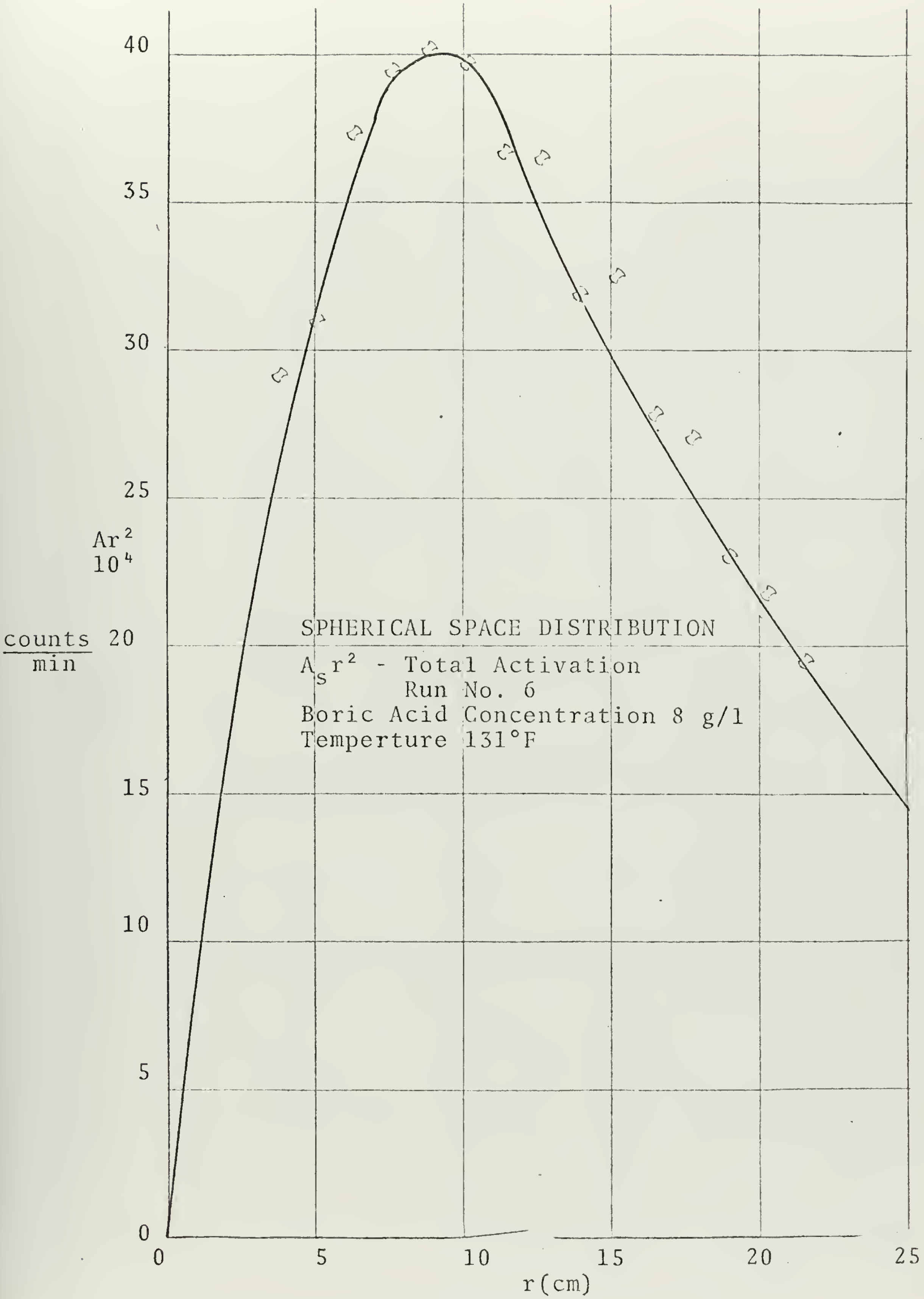

SPHERICAL SPACE DISTRIBUTION
$A_s r^2$ - Total Activation
Run No. 6
Boric Acid Concentration 8 g/l
Temperture 131°F
$\frac{Ar^2}{10^4}$
$\frac{\text{counts}}{\text{min}}$
0
5
10
15
20
25
30
35
40
0
5
10
15
20
25
r(cm)

FIGURE 11

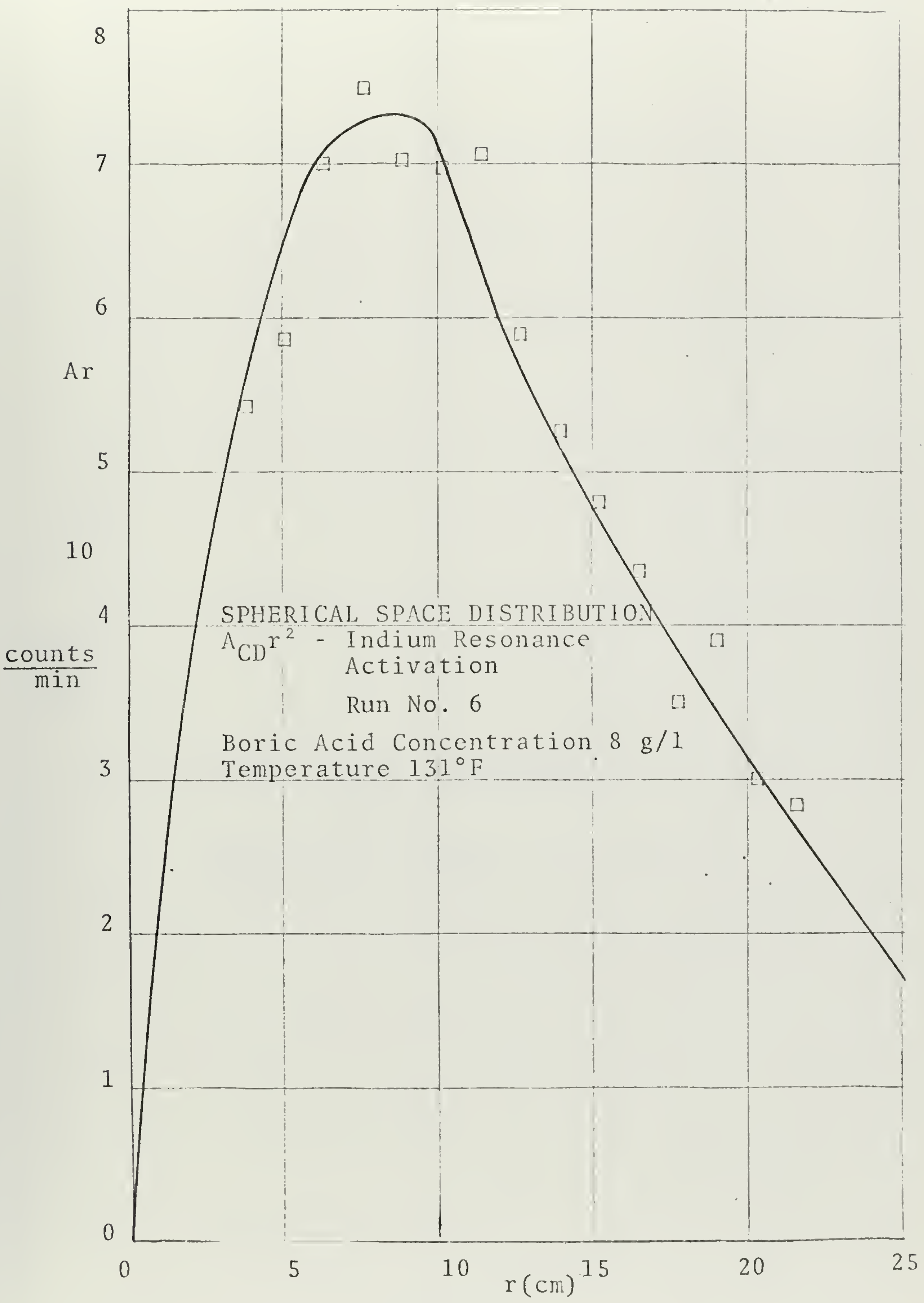

SPHERICAL SPACE DISTRIBUTION
$A_{CD}r^2$ - Indium Resonance Activation
Run No. 6
Boric Acid Concentration 8 g/l
Temperature 131°F
Ar
10
counts/min
8
7
6
5
4
3
2
1
0
0
5
10
15
20
25
r(cm)

FIGURE 12

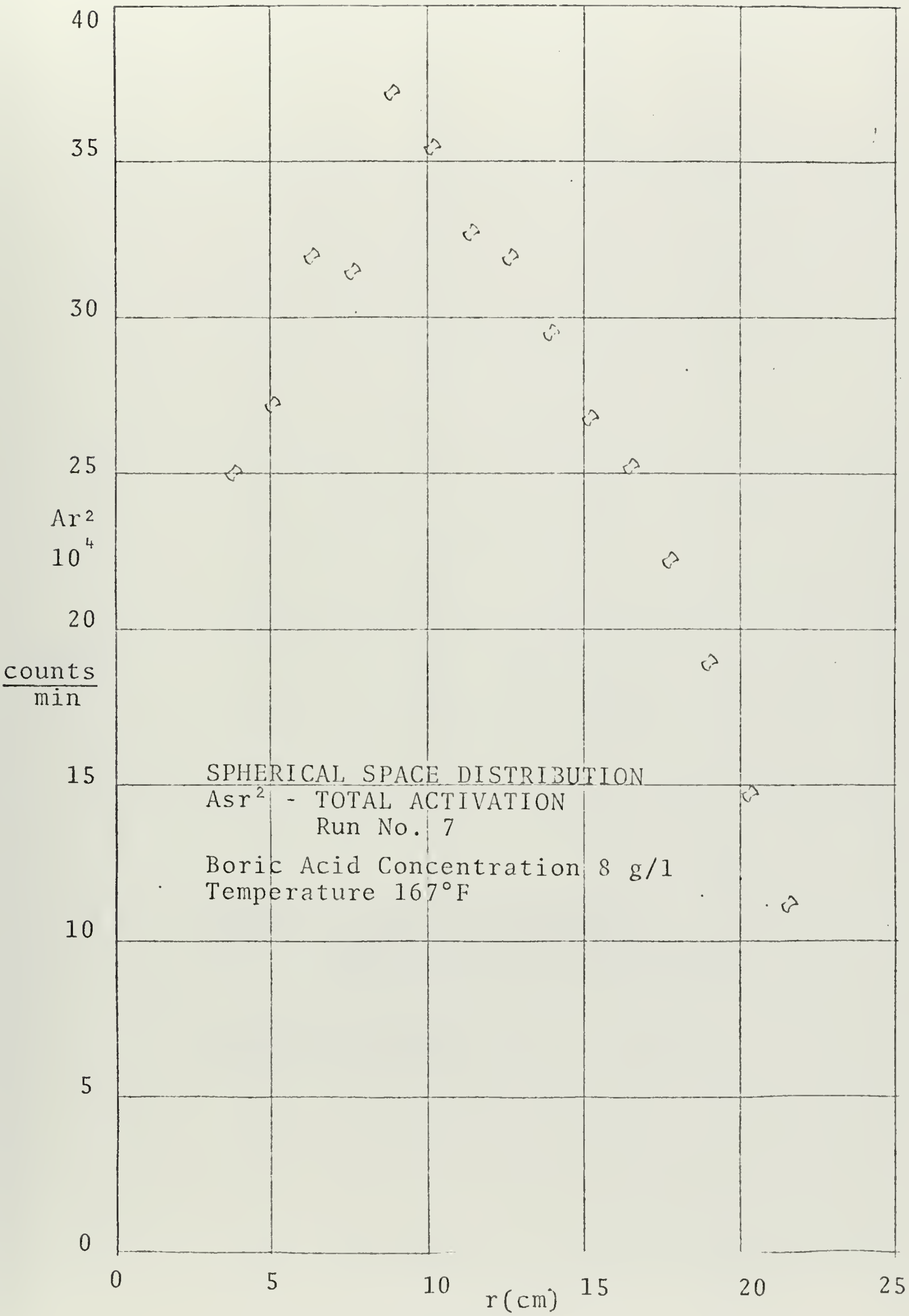
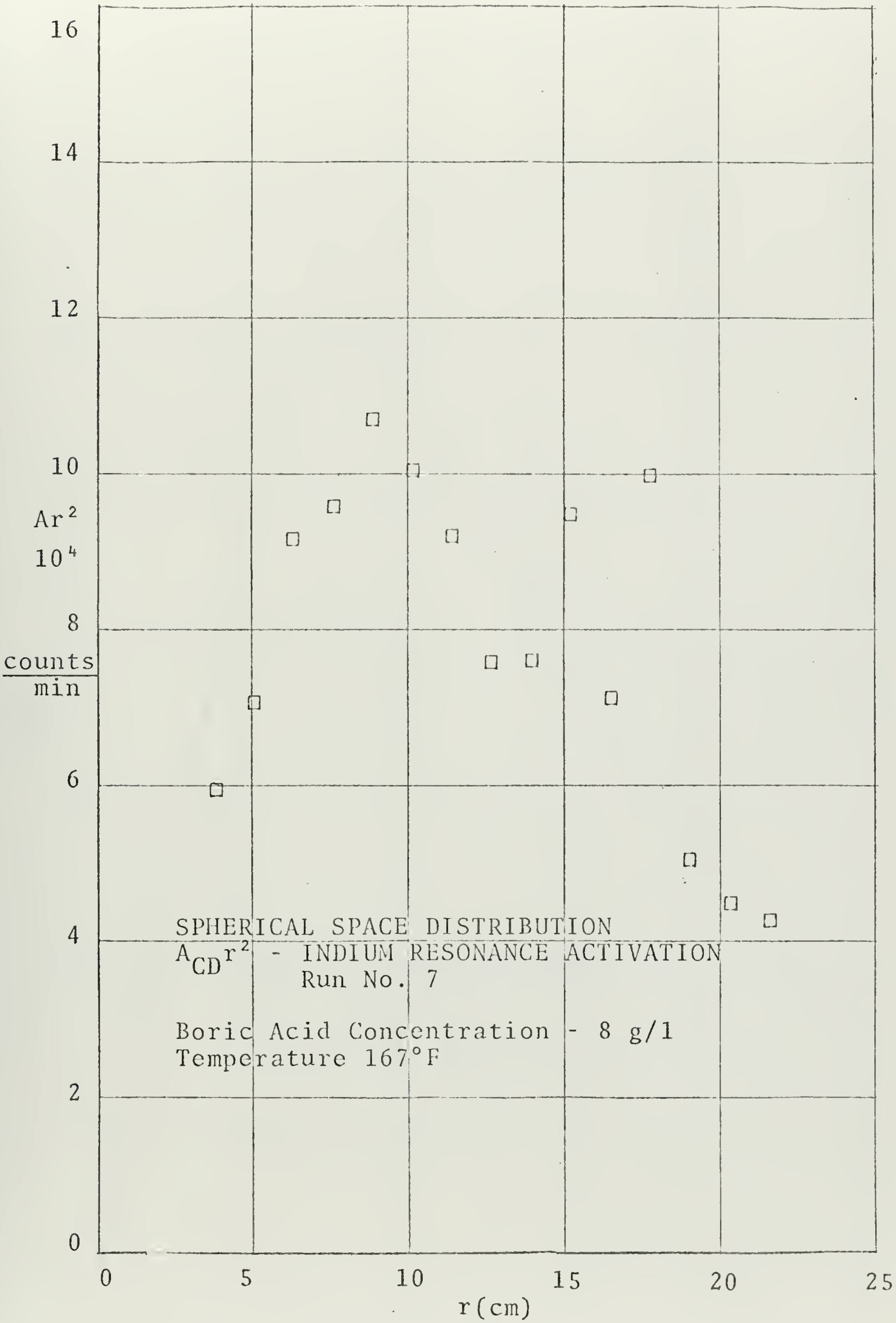

40
35
30
25
Ar²
10⁴
20
counts
min
15
10
5
0
0
5
10
15
20
25
r(cm)
SPHERICAL SPACE DISTRIBUTION
Asr² - TOTAL ACTIVATION
Run No. 7
Boric Acid Concentration 8 g/1
Temperature 167°F

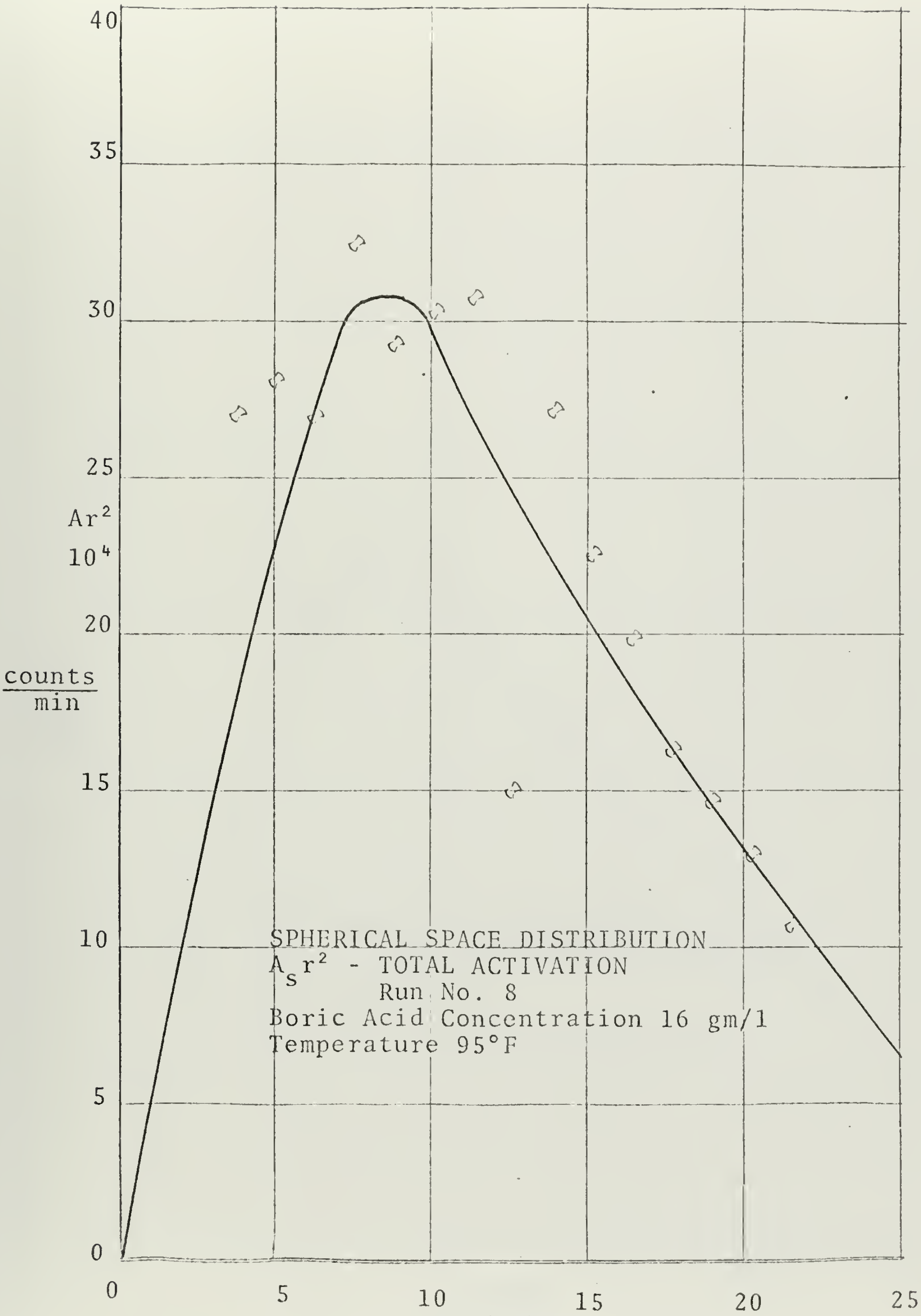
FIGURE 13



SPHERICAL SPACE DISTRIBUTION
$A_{CD}r^2$ - INDIUM RESONANCE ACTIVATION
Run No. 7

Boric Acid Concentration - 8 g/1
Temperature 167°F

FIGURE 14



SPHERICAL SPACE DISTRIBUTION
$A_s r^2$ - TOTAL ACTIVATION
Run No. 8
Boric Acid Concentration 16 gm/1
Temperature 95°F

FIGURE 15

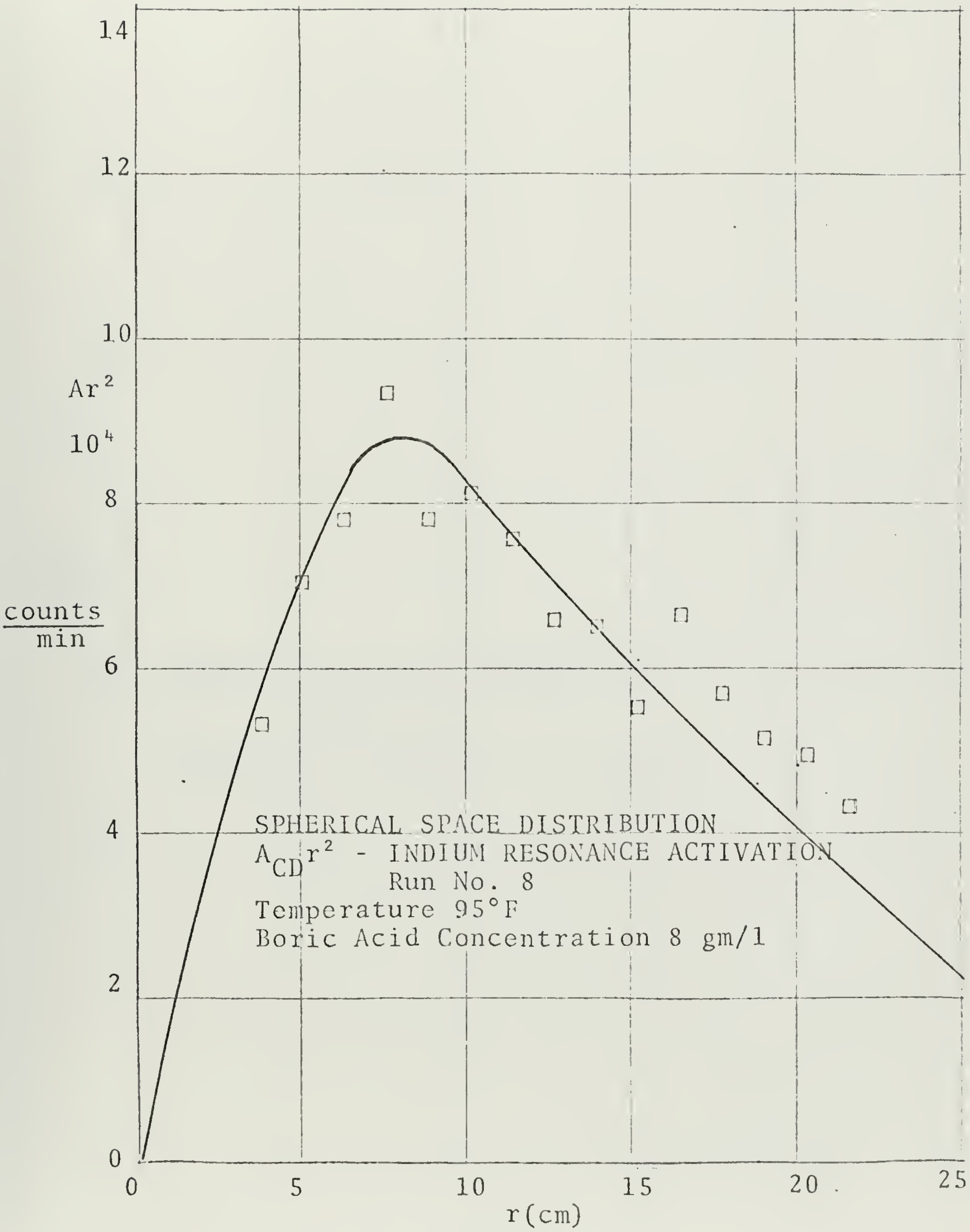

14
12
10
Ar²
10⁴
8
counts/min
6
4
2
0
0
5
10
15
20
25
r(cm)
SPHERICAL SPACE DISTRIBUTION
A_CD r² - INDIUM RESONANCE ACTIVATION
Run No. 8
Temperature 95°F
Boric Acid Concentration 8 gm/1

FIGURE 16

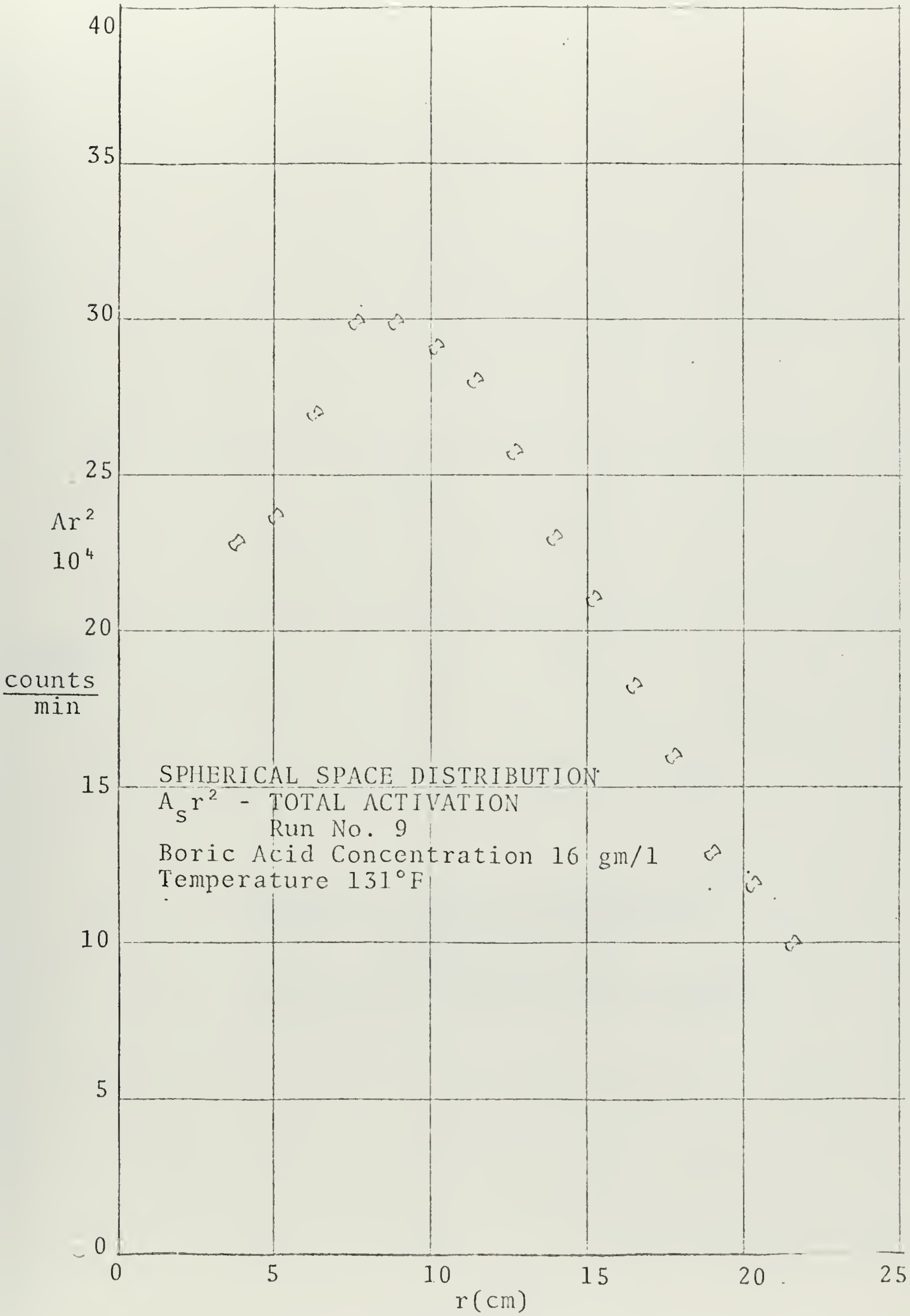

40
35
30
25
Ar^2
10^4
20
counts/min
15
10
5
0
0
5
10
15
20
25
r(cm)
SPHERICAL SPACE DISTRIBUTION
A$_s$r^2 - TOTAL ACTIVATION
Run No. 9
Boric Acid Concentration 16 gm/l
Temperature 131°F

FIGURE 17

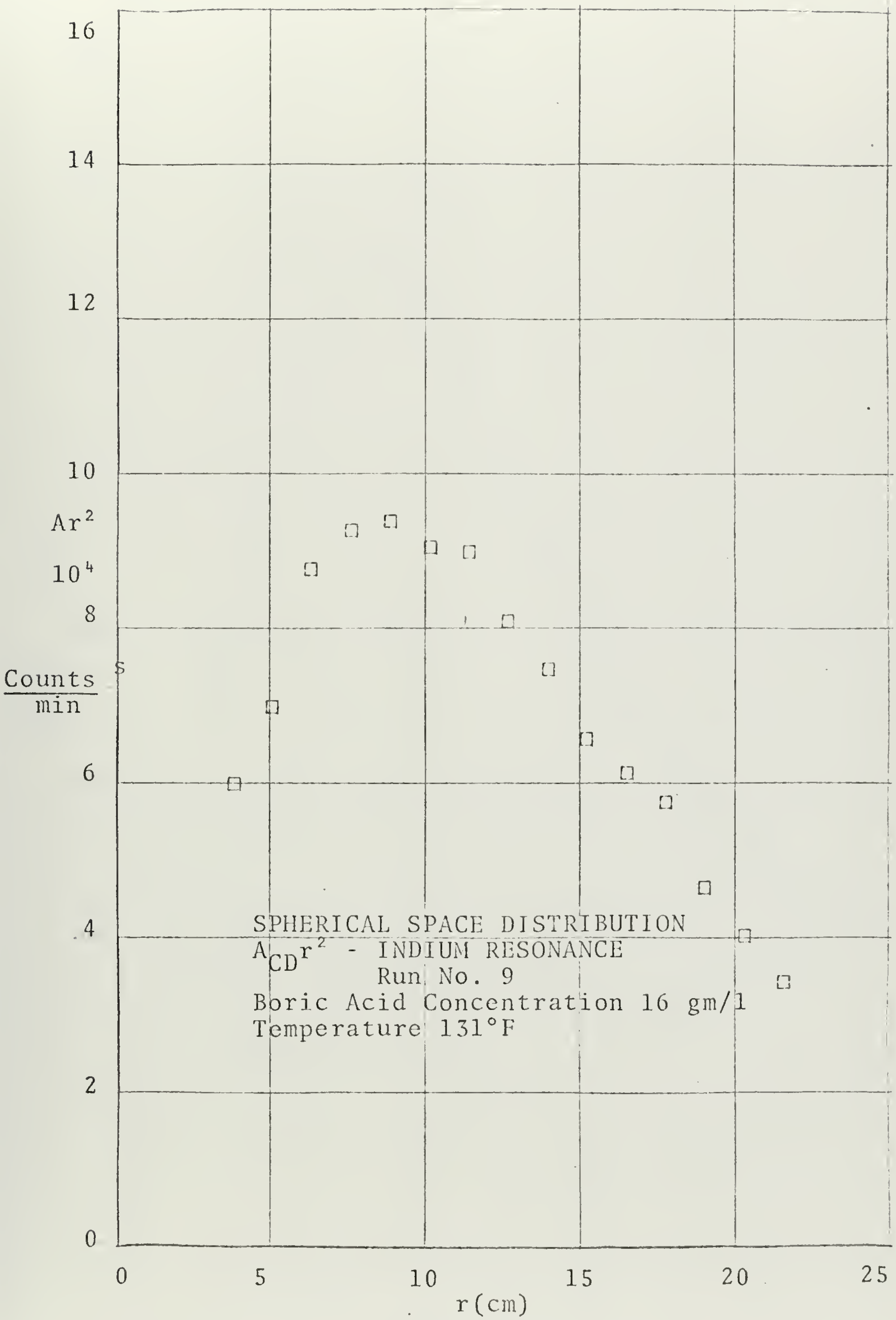

16
14
12
10
$\frac{Ar^2}{10^4}$
8
$\frac{\text{Counts}}{\text{min}}$
6
4
2
0
0
5
10
15
20
25
r(cm)
SPHERICAL SPACE DISTRIBUTION
$A_{CD}r^2$ - INDIUM RESONANCE
Run No. 9
Boric Acid Concentration 16 gm/l
Temperature 131°F

FIGURE 18

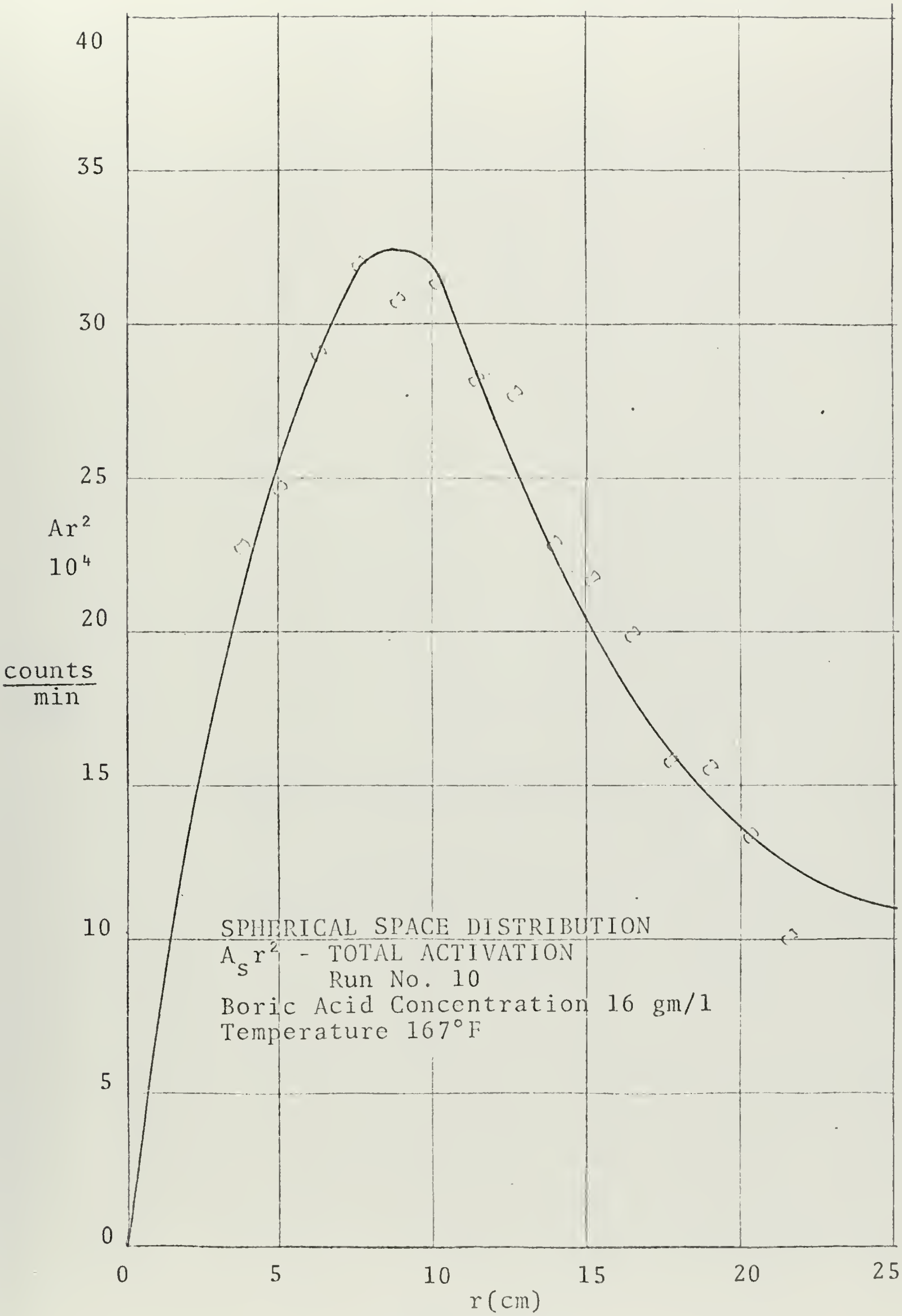

40
35
30
25
20
15
10
5
0
Ar²
10⁴
counts
min
0
5
10
15
20
25
r(cm)
SPHERICAL SPACE DISTRIBUTION
$A_s r^2$ - TOTAL ACTIVATION
Run No. 10
Boric Acid Concentration 16 gm/l
Temperature 167°F

FIGURE 19

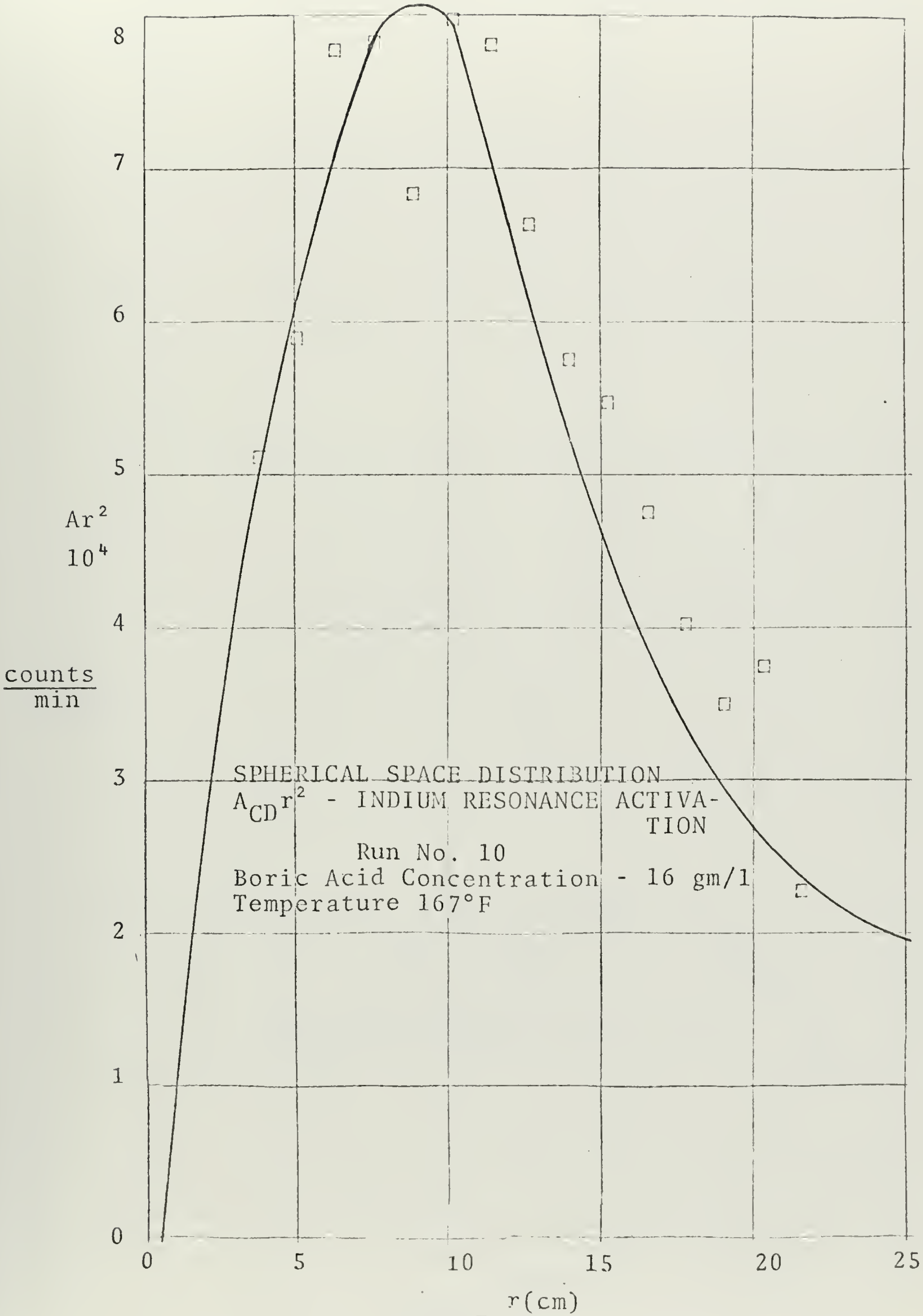

SPHERICAL SPACE DISTRIBUTION
$A_{CD}r^2$ - INDIUM RESONANCE ACTIVATION
Run No. 10
Boric Acid Concentration - 16 gm/l
Temperature 167°F
$\frac{Ar^2}{10^4}$
$\frac{\text{counts}}{\text{min}}$
0
1
2
3
4
5
6
7
8
0
5
10
15
20
25
r(cm)

FIGURE 20

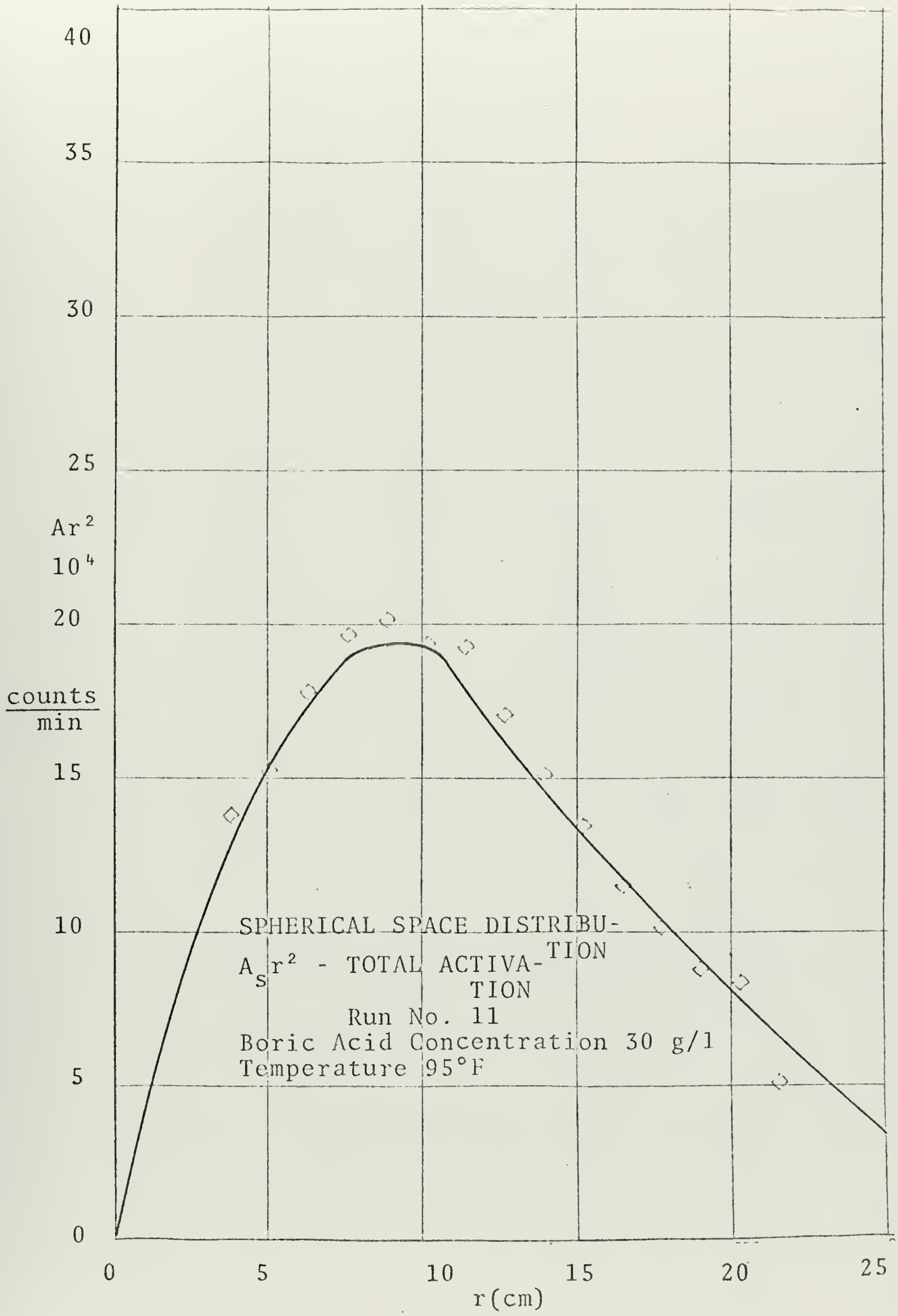

40
35
30
25
$\frac{Ar^2}{10^4}$
20
$\frac{counts}{min}$
15
10
5
0
0
5
10
15
20
25
r(cm)
SPHERICAL SPACE DISTRIBUTION
$A_s r^2$ - TOTAL ACTIVATION
Run No. 11
Boric Acid Concentration 30 g/l
Temperature 95°F

FIGURE 21

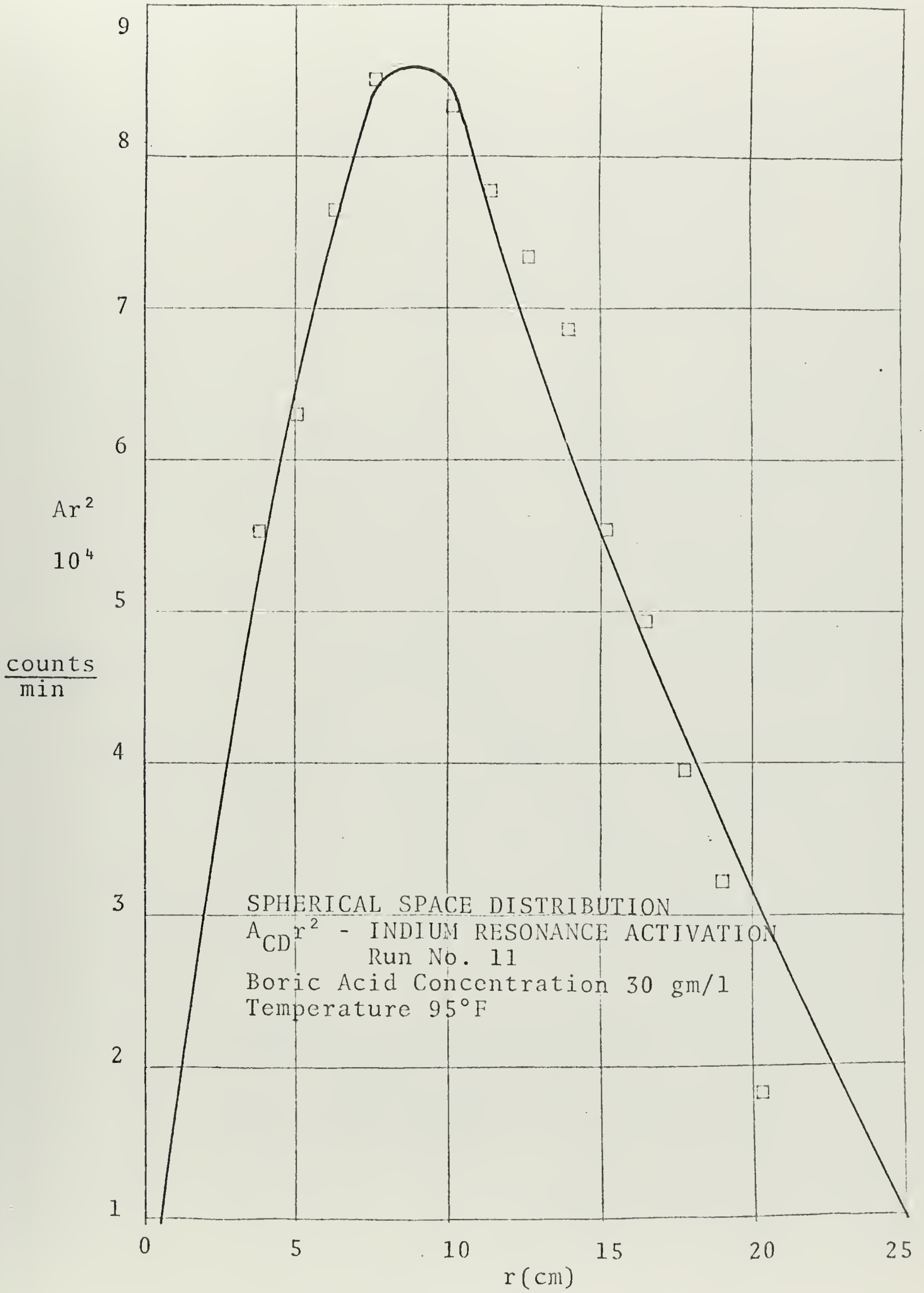

9
8
7
6
5
4
3
2
1
Ar^2
10^4
counts/min
0
5
10
15
20
25
r(cm)
SPHERICAL SPACE DISTRIBUTION
$A_{CD}r^2$ - INDIUM RESONANCE ACTIVATION
Run No. 11
Boric Acid Concentration 30 gm/l
Temperature 95°F

FIGURE 22

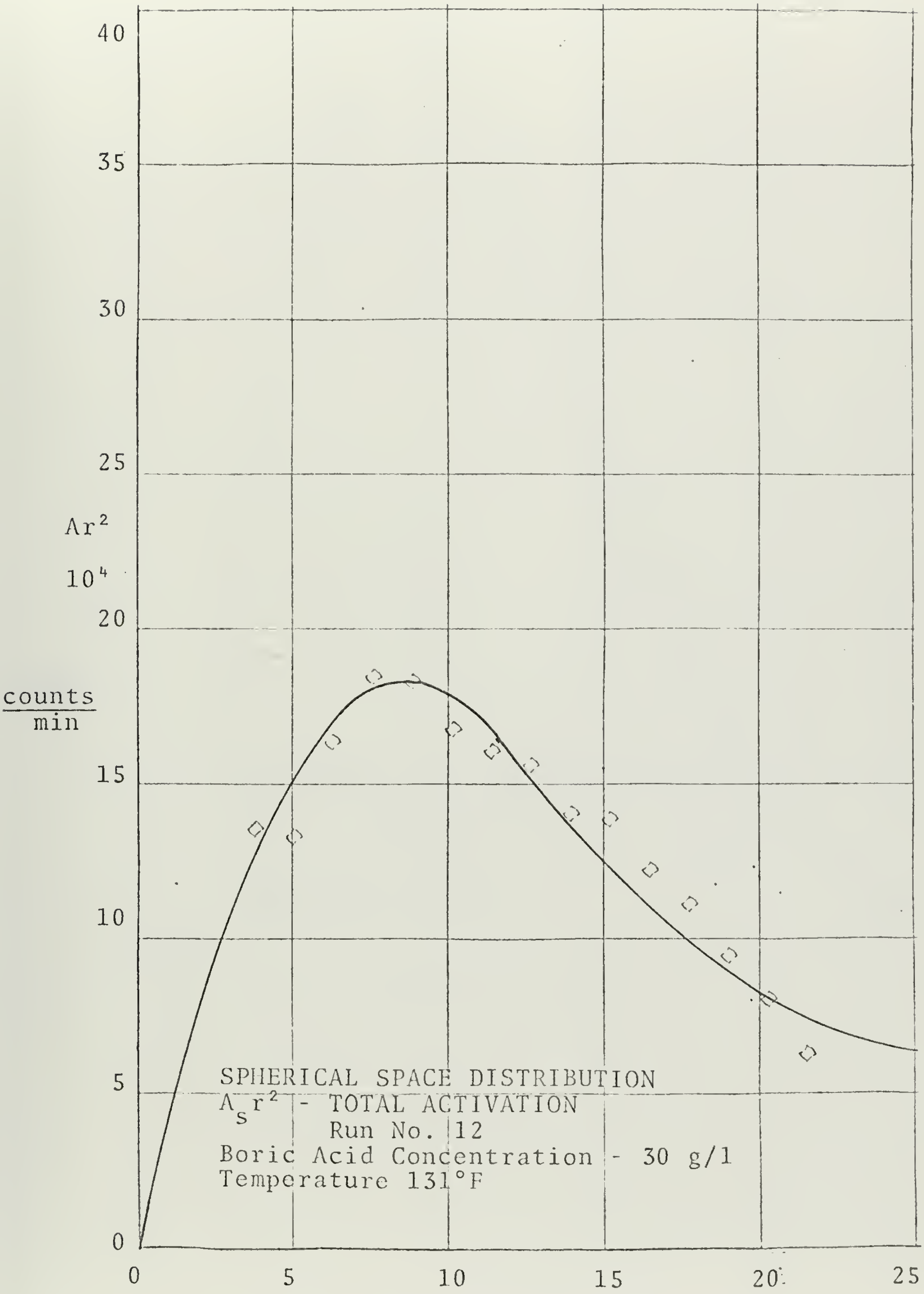

40
35
30
25
Ar^2
10^4
20
$\frac{\text{counts}}{\text{min}}$
15
10
5
0
0
5
10
15
20
25
r(cm)
SPHERICAL SPACE DISTRIBUTION
$A_s r^2$ - TOTAL ACTIVATION
Run No. 12
Boric Acid Concentration - 30 g/1
Temperature 131°F

FIGURE 23

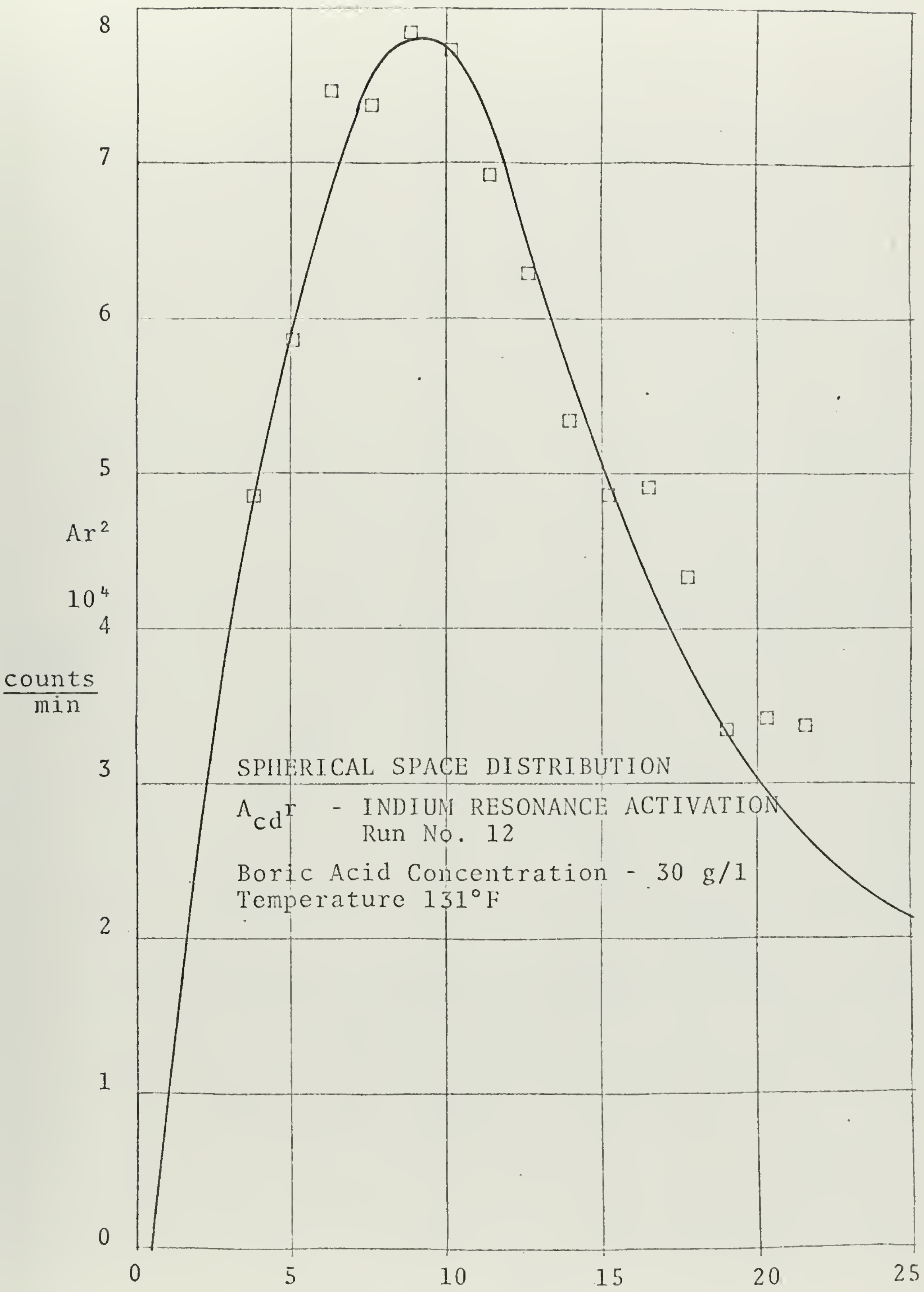

8
7
6
5
4
3
2
1
0
Ar²
10⁴
counts
min
0
5
10
15
20
25
r(cm)
SPHERICAL SPACE DISTRIBUTION
A_cd r - INDIUM RESONANCE ACTIVATION
Run No. 12
Boric Acid Concentration - 30 g/l
Temperature 131°F

FIGURE 24

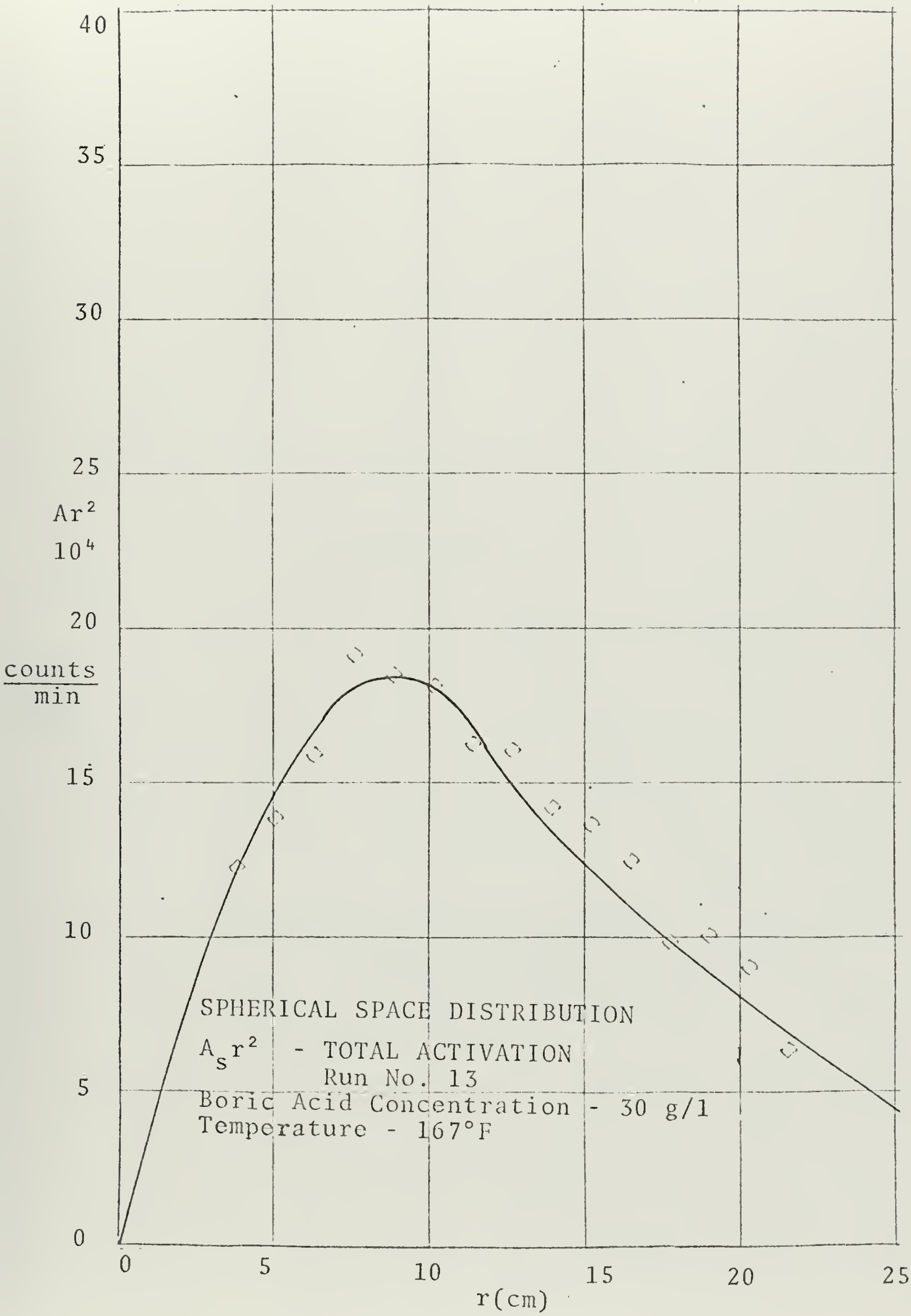

40
35
30
25
Ar²
10⁴
20
counts
min
15
10
5
0
0
5
10
15
20
25
r(cm)
SPHERICAL SPACE DISTRIBUTION
Asr² - TOTAL ACTIVATION
Run No. 13
Boric Acid Concentration - 30 g/l
Temperature - 167°F

FIGURE 25

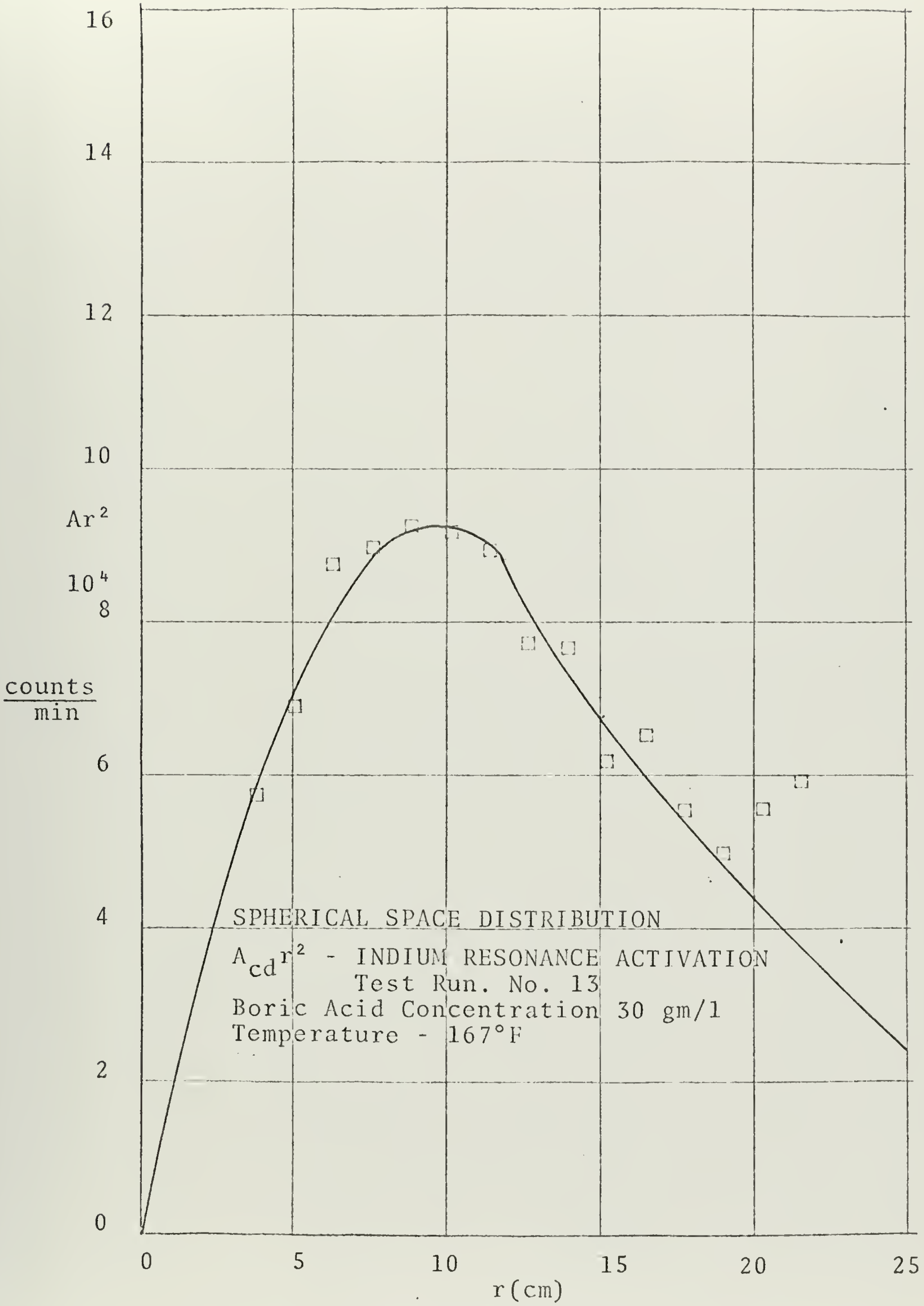

16
14
12
10
Ar^2
10^4
8
counts/min
6
4
2
0
0
5
10
15
20
25
r(cm)
SPHERICAL SPACE DISTRIBUTION
$A_{cd}r^2$ - INDIUM RESONANCE ACTIVATION
Test Run. No. 13
Boric Acid Concentration 30 gm/1
Temperature - 167°F

FIGURE 26

APPENDIX C

ACTIVATION DATA FOR POISON RUNS

TABLE V

H_3BO_3 CONCENTRATION 8.0 g/1; INDIUM RESONANCE ACTIVATION TEMPERATURE 95°F

r(cm)	A_{CD}(CPM)	MEAN COUNT	STANDARD DEVIATION
3.81	4338.9062	3510.6030	59.25
5.08	2691.9985	2172.0639	46.60
6.35	2028.5357	1631.6850	40.39
7.62	1447.7858	1160.9482	34.07
8.89	1094.8874	8713.8183	29.51
10.16	769.0697	612.2907	24.74
11.43	580.6441	460.4277	21.45
12.70	423.2587	334.1813	18.28
13.97	315.7761	248.0522	15.74
15.24	235.0387	183.7874	13.55
16.51	171.5650	133.4304	11.55
17.78	127.5265	98.6032	9.92
19.05	89.6837	68.9076	8.30
20.32	67.0308	51.1201	7.14
21.59	75.2695	40.5087	6.36

TABLE VI

H_3BO_3 CONCENTRATION 8.0 g/1; TOTAL ACTIVATION TEMPERATURE 95°F

r(cm)	A_S(CPM)	MEAN COUNT	STANDARD DEVIATION
3.81	11509.8781	13952.5742	118.12
5.08	9497.4623	8464.7929	92.00
6.35	7423.1657	6507.8710	80.67
7.62	5566.3006	4894.4101	69.96
8.89	4071.2426	3612.4257	60.10
10.16	2972.1105	2627.4343	51.25
11.43	2250.4948	1981.6005	44.51
12.70	1729.0450	1505.0419	38.79
13.97	1235.7078	1077.4638	32.82
15.24	989.6018	858.1154	29.29
16.51	732.5951	622.7670	24.95
17.78	522.9899	473.8107	21.76
19.05	419.0863	356.7763	18.88
20.32	322.2161	272.4084	16.50
21.59	248.4556	208.4776	14.43

TABLE VII

H_3BO_3 CONCENTRATION 8.0 g/1; INDIUM RESONANCE ACTIVATION TEMPERATURE 131°F

r(cm)	A_{CD}(CPM)	MEAN COUNT	STANDARD DEVIATION
3.81	3740.3436	3040.1044	55.13
5.08	2271.1732	1841.5061	42.91
6.35	1736.7794	1404.8835	37.48
7.62	1290.1232	1041.6748	32.25
8.89	889.0577	715.0063	26.73
10.16	675.6499	541.6247	23.27
11.43	540.5715	431.8361	20.78
12.70	365.6290	290.9912	17.05
13.97	269.6938	213.8565	14.62
15.24	207.0582	163.2117	12.77
16.51	159.8396	124.7460	11.16
17.78	110.9198	86.0412	9.27
19.05	107.6441	83.0443	9.11
20.32	72.8171	55.8133	7.47
21.59	60.8034	46.2799	6.80

TABLE VIII

H_3BO_3 CONCENTRATION 8.0 g/1; TOTAL ACTIVATION TEMPERATURE 131°F

r(cm)	A_S(CPM)	MEAN COUNT	STANDARD DEVIATION
3.81	20109.0553	18046.6484	134.33
5.08	11566.5587	10350.9726	101.73
6.35	8869.6275	7913.3593	88.95
7.62	6536.7874	5812.9609	76.24
8.89	4962.5813	4397.5390	66.31
10.16	3720.1893	3284.1132	57.30
11.43	2812.3892	2472.5913	49.72
12.70	2091.6808	1830.8740	42.78
13.97	1610.7691	1403.2451	37.45
15.24	1271.6344	1101.6093	33.19
16.51	935.2484	806.1274	28.39
17.78	729.9680	625.0952	25.00
19.05	546.4106	465.1699	21.56
20.32	412.6101	348.8295	18.67
21.59	327.0331	274.4113	16.56

TABLE IX

H_3BO_3 CONCENTRATION 8.0 g/1; INDIUM RESONANCE ACTIVATION
TEMPERATURE 167°F

r(cm)	A_{CD}(CPM)	MEAN COUNT	STANDARD DEVIATION
3.81	4268.5135	3436.8632	58.62
5.08	2863.6486	2299.7617	47.95
6.35	2335.1988	1870.2941	43.24
7.62	1668.7725	1332.7524	36.50
8.89	1369.9945	1090.5432	33.02
10.16	973.7141	772.9123	27.80
11.43	697.1962	551.6057	23.48
12.70	475.3571	374.7990	19.35
13.97	388.4696	303.0793	17.40
15.24	392.8802	255.2706	15.97
16.51	264.9628	205.1085	14.32
17.76	316.3616	162.4721	12.74
19.05	139.1435	106.7854	10.33
20.32	107.4450	82.6591	9.09
21.59	89.9828	68.8904	8.30

TABLE X

H_3BO_3 CONCENTRATION 8.0 g/1; TOTAL ACTIVATION
TEMPERATURE 167°F

r(cm)	A_S(CPM)	MEAN COUNT	STANDARD DEVIATION
3.81	20692.8863	18570.5976	136.27
5.08	12481.0852	11170.0156	105.68
6.35	9169.2326	8180.6640	90.44
7.62	6277.5951	5582.4726	74.71
8.89	5344.6326	4736.0898	68.81
10.16	3937.0296	3475.5358	58.95
11.43	2886.7369	2537.9560	50.37
12.70	2290.5178	2004.9187	44.77
13.97	1768.2372	1540.4257	39.24
15.24	1368.2429	1185.8757	34.43
16.51	1108.0042	955.0327	30.90
17.78	861.6697	738.2927	27.17
19.05	659.6030	561.5327	23.69
20.32	477.2240	403.4556	20.08
21.59	346.5687	290.9023	17.05

TABLE XI

H_3BO_3 CONCENTRATION 16 g/1; INDIUM RESONANCE ACTIVATION
TEMPERATURE 95°F

r(cm)	A_{CD}(CPM)	MEAN COUNT	STANDARD DEVIATION
3.81	4116.3652	3151.4687	56.13
5.08	3034.3682	2334.3879	48.31
6.35	2185.4791	1689.1000	41.09
7.62	1419.0948	1101.6096	33.19
8.89	1164.1740	907.5075	30.12
10.16	755.3704	591.1831	24.31
11.43	558.3584	438.6540	20.94
12.70	455.3512	359.0251	18.94
13.97	309.0079	244.4800	15.63
15.24	227.6572	180.7092	13.44
16.51	220.7544	175.7788	13.25
17.78	209.2343	167.1031	12.92
19.05	131.9818	105.7061	10.28
20.32	130.0777	104.4638	10.22
21.59	117.1275	94.3071	9.71

TABLE XII

H_3BO_3 CONCENTRATION 16 g/1; TOTAL ACTIVATION
TEMPERATURE 95°F

r(cm)	A_S(CPM)	MEAN COUNT	STANDARD DEVIATION
3.81	18626.1055	9497.1953	97.45
5.08	10895.5391	5582.4882	74.71
6.35	6685.8054	3441.4116	58.66
7.62	5595.1975	2890.9396	53.76
8.89	3702.6471	1922.2897	43.84
10.16	2939.2058	1532.0256	39.14
11.43	2357.4266	1233.4499	35.12
12.70	9306.7335	804.2429	28.35
13.97	1391.1851	733.0488	27.07
15.24	970.9109	513.2778	22.65
16.51	728.9893	386.5915	19.66
17.78	516.2110	274.5700	16.57
19.05	404.9721	216.0157	14.69
20.32	313.6666	167.7666	12.95
21.59	230.3158	123.5047	11.11

TABLE XIII

H_3BO_3 CONCENTRATION 16 g/l; INDIUM RESONANCE ACTIVATION
TEMPERATURE 131°F

r(cm)	A_{CD}(CPM)	MEAN COUNT	STANDARD DEVIATION
3.81	4133.0768	3164.2629	56.25
5.08	2710.5077	2085.2368	45.66
6.35	2175.8190	1681.6340	41.00
7.62	1594.8277	1238.0266	35.18
8.89	1188.0543	926.1230	30.43
10.16	876.8356	686.2463	26.19
11.43	687.5132	540.1201	23.24
12.70	501.3977	395.3308	19.88
13.97	382.6678	302.7580	17.39
15.24	282.6519	224.3627	14.97
16.51	224.8465	179.0371	13.38
17.78	181.8621	145.2425	12.05
19.05	127.9392	102.4683	10.12
20.32	97.5775	78.3633	8.85
21.59	73.5245	59.1995	7.69

TABLE XIV

H_3BO_3 CONCENTRATION 16 g/l; TOTAL ACTIVATION
TEMPERATURE 131°F

r(cm)	A_S(CPM)	MEAN COUNT	STANDARD DEVIATION
3.81	15732.0113	8021.5351	89.56
5.08	9167.6452	4697.1757	68.53
6.35	6695.2128	3446.2539	58.70
7.62	5151.0925	2663.1140	51.60
8.89	3788.3850	1966.8022	44.34
10.16	2832.8391	1476.5834	38.42
11.43	2144.8511	1122.2265	33.49
12.70	1595.8782	838.0163	28.94
13.97	1177.5317	620.4697	24.90
15.24	906.2015	479.0686	21.88
16.51	668.0390	354.2690	18.82
17.78	505.9825	269.1296	16.40
19.05	354.5358	189.1125	13.75
20.32	287.2258	153.6246	12.39
21.59	213.6016	114.5419	10.70

TABLE XV

H_3BO_3 CONCENTRATION 16 g/1; INDIUM RESONANCE ACTIVATION TEMPERATURE 167°F

r(cm)	A_{CD}(CPM)	MEAN COUNT	STANDARD DEVIATION
3.81	4213.6345	3225.9375	56.79
5.08	2672.1145	2055.7004	45.33
6.35	2102.6545	1625.0871	40.31
7.62	1520.5024	1180.3295	34.35
8.89	1145.9158	893.2749	29.88
10.16	869.8834	680.8051	26.09
11.43	673.7225	529.2858	23.00
12.70	492.3515	388.1984	19.70
13.97	365.0609	288.8278	16.90
15.24	278.6658	221.1986	14.87
16.51	211.2086	168.1763	12.96
17.78	158.9448	126.9398	11.26
19.05	123.8967	99.2307	9.96
20.32	90.8913	72.9937	8.54
21.59	70.3152	56.6154	7.52

TABLE XVI

H_3BO_3 CONCENTRATION 16 g/1; TOTAL ACTIVATION TEMPERATURE 167°F

r(cm)	A_S(CPM)	MEAN COUNT	STANDARD DEVIATION
3.81	15683.6585	7996.8828	89.42
5.08	9559.2448	4897.8164	69.98
6.35	7208.4950	3710.4577	60.91
7.62	5502.6384	2844.8632	53.33
8.89	3895.1716	2022.2421	44.96
10.16	2960.5430	1543.1474	39.28
11.43	2208.6044	1155.5834	33.99
12.70	1682.5217	883.5139	29.72
13.97	1226.8919	646.4787	25.42
15.24	936.2943	494.9772	22.24
16.51	698.5095	370.4277	19.24
17.78	500.3817	266.1506	16.31
19.05	395.2241	210.8160	14.51
20.32	299.4661	160.1714	12.65
21.59	216.0595	115.8599	10.76

TABLE XVII

H_3BO_3 CONCENTRATION 30 g/l; INDIUM RESONANCE ACTIVATION
TEMPERATURE 95°F

r(cm)	A_{CD}(CPM)	MEAN COUNT	STANDARD DEVIATION
3.81	3814.3995	1752.1708	41.85
5.08	2444.9645	1128.5703	33.59
6.35	1898.0324	880.1640	29.66
7.62	1466.2170	682.9135	26.13
8.89	1152.9376	539.2492	23.22
10.16	807.3318	379.1101	19.47
11.43	595.1468	280.5332	16.74
12.70	455.3512	215.4151	14.67
13.97	351.5190	166.8683	12.91
15.24	238.8134	113.7388	10.66
16.51	181.2051	86.5722	9.30
17.78	125.2512	60.0184	7.74
19.05	88.8686	42.7057	6.53
20.32	44.0997	21.2496	4.60
21.59	17.3741	8.3934	2.89

TABLE XVIII

H_3BO_3 CONCENTRATION 30 g/l; TOTAL ACTIVATION
TEMPERATURE 95°F

r(cm)	A_S(CPM)	MEAN COUNT	STANDARD DEVIATION
3.81	9512.9576	4850.5273	69.64
5.08	5909.7507	3027.9460	55.02
6.35	4424.9625	2277.6787	47.72
7.62	3384.5104	1749.7912	41.83
8.89	2552.1833	1325.0078	36.40
10.16	1875.4493	965.1225	31.06
11.43	1474.2346	767.2319	27.69
12.70	1058.7325	556.7866	23.59
13.97	773.8019	408.3164	20.20
15.24	579.9679	307.0202	17.52
16.51	422.9913	225.1728	15.00
17.78	322.3804	171.6843	13.10
19.05	242.7463	129.6355	11.38
20.32	202.5797	108.4727	10.41
21.59	110.3097	59.2159	7.69

TABLE XIX

H_3BO_3 CONCENTRATION 30 g/1; INDIUM RESONANCE ACTIVATION
TEMPERATURE 131°F

r(cm)	A_{CD}(CPM)	MEAN COUNT	STANDARD DEVIATION
3.81	4032.5113	3048.0051	55.20
5.08	2261.6839	2021.6328	44.96
6.35	2034.2463	1574.2250	39.67
7.62	1441.6142	1120.4519	33.47
8.89	1119.1448	871.3825	29.51
10.16	845.8544	660.1320	25.69
11.43	639.5929	501.1230	22.38
12.70	483.9967	380.6340	19.50
13.97	355.0934	280.2563	16.74
15.24	272.6566	215.9255	14.69
16.51	217.1437	172.5205	13.13
17.78	161.9829	129.0929	11.36
19.05	120.0964	95.9932	9.79
20.32	93.7458	75.1415	8.66
21.59	73.6595	59.1995	7.69

TABLE XX

H_3BO_3 CONCENTRATION 30 g/1; TOTAL ACTIVATION
TEMPERATURE 131°F

r(cm)	A_S(CPM)	MEAN COUNT	STANDARD DEVIATION
3.81	9348.0959	4766.4648	69.03
5.08	5167.0679	2647.4218	51.45
6.35	4059.7207	2089.6765	45.71
7.62	3025.5249	1554.2170	39.42
8.89	2255.1747	1171.4912	34.22
10.16	1693.3000	883.1005	29.71
11.43	1280.2822	670.5717	25.89
12.70	969.5395	509.6274	22.51
13.97	733.6620	386.9528	19.67
15.24	572.7375	303.0563	17.40
16.51	431.5252	229.0411	15.13
17.78	323.7266	172.3308	13.12
19.05	242.8408	129.6355	11.38
20.32	187.9917	100.6241	10.03
21.59	138.5682	74.3591	8.62

TABLE XXI

H_3BO_3 CONCENTRATION 30 g/1; INDIUM RESONANCE ACTIVATION TEMPERATURE 167°F

r(cm)	A_{CD}(CPM)	MEAN COUNT	STANDARD DEVIATION
3.81	3956.9440	3029.4165	55.04
5.08	2678.0214	2060.2446	45.38
6.35	2029.5357	1568.5754	39.60
7.62	1547.6544	1201.4069	34.66
8.89	1174.0066	915.1723	30.25
10.16	889.3505	696.0410	26.38
11.43	684.7551	537.9533	23.19
12.70	519.7670	409.8142	20.24
13.97	393.3046	310.2597	17.61
15.24	306.2453	242.2943	15.56
16.51	239.2349	189.8993	13.78
17.78	175.6441	139.8590	11.82
19.05	137.7631	110.0232	10.48
20.32	107.9603	85.8811	9.26
21.59	80.4186	64.5832	8.03

TABLE XXII

H_3BO_3 CONCENTRATION 30 g/1; TOTAL ACTIVATION TEMPERATURE 167°F

r(cm)	A_S(CPM)	MEAN COUNT	STANDARD DEVIATION
3.81	8459.7042	4365.5546	66.07
5.08	5483.4342	2841.7880	53.30
6.35	4247.0050	2209.9780	47.01
7.62	3191.6215	1656.6054	40.70
8.89	2346.1385	1230.7382	35.08
10.16	1762.6128	927.8654	30.46
11.43	1344.7866	710.2744	26.65
12.70	997.1895	528.3569	22.98
13.97	742.7238	394.7204	19.86
15.24	588.4379	313.6276	17.70
16.51	440.6199	235.4891	15.34
17.78	91.4371	48.9967	6.99
19.05	242.5287	130.2845	11.41
20.32	200.2300	107.8186	10.38
21.59	141.4392	76.3347	8.73

APPENDIX D

COMPUTER PROGRAM NO. 1

THE PURPOSE OF THIS PROGRAM IS TO (1) CORRECT THE COUNTING DATA FOR NORMALIZED FOIL WEIGHT, ABSORPTION OF INDIUM RESONANCE NEUTRONS BY THE CADMIUM COVER AND COUNTER RESOLVING TIME, (2) COMPUTE THE MEAN COUNTING RATE AND, FROM THIS, DETERMINE THE STANDARD DEVIATION, (3) COMPUTE THE PRODUCTS AS*R**2,AS*R**4,LOG AS*R**2, AS(CD)*R**2, AS(CD)*R**4, AND (4) PLOT GRAPHS OF THE ABOVE PRODUCTS VERSUS R, THE DISTANCE FROM THE SOURCE.

PROGRAM NOTATION

D1	DECAY CONSTANT FOR INDIUM-116
T	COUNTER RESOLVING TIME
POS	DISTANCE FROM SOURCE
X	FOIL IRRADIATION TIME
Y	WAITING TIME
Z	WAITING TIME PLUS COUNTING TIME
W	CORRECTION FACTOR FOR FOIL WEIGHT
C1	FOIL COUNTS
SAT	SATURATED ACTIVITY
SIGMA	STANDARD DEVIATION
AMEAN	MEAN COUNTING RATE
F	CADMIUM CORRECTION FACTOR

```
   IMPLICIT REAL*8(A-H,O-Z)
   WRITE(6,1)
 1 FORMAT(T5,'DISTANCE',T25,'SAT ACTIVITY',T56,'MEAN',
  1T87,'SIGMA'//)
   REAL AC,AD,AA,BB,DISTA,DISTC,B,SUM,C,D,E,U,V,D1,C1,B1
   DIMENSION AC(25),AD(25),AA(25),BB(25),DISTA(25),DISTC(
   25), B(3),SUM
  1(4),C(3,3),D(9),E(3),U(402),V(401)
   REAL LABEL1/4H    /,LABEL2/4H    /,LABEL3/4H    /,LABE
   L4/4H    /
   REAL*8 ITITLE(12)

   RUN NUMBER THIRTEEN

   COMPUTATION OF SATURATED ACTIVITY OF INDIUM FOILS AND
   PRODUCTS AS*R**2 AND AS*R**4

   D1=1.28D-2
   T=6.0D-6
   DO50 N=1,15
   READ(5,2) POS,C1,X,Y,Z
 2 FORMAT(5F9.0)
   READ(5,6) W
 6 FORMAT(1F9.0)
   DIST=(POS-1.750)*0.254D01
   C1=W*3.0*C1/(1.0D0-C1*T)
   ASAT=D1*C1/((1.0D0-DEXP(-D1*X))*(DEXP(-D1*Y)-DEXP(-D1*
```

```
     Z)))
     SAT=ASAT
     AMEAN=C1/3.0
     SIGMA=AMEAN**0.5D0
     F=1.11D0
     FSAT=F*SAT
     WRITE(6,4) DIST,FSAT,AMEAN,SIGMA
   4 FORMAT(T6,F5.2,6X,D25.16,6X,D25.16,6X,D25.16)
     A=FSAT*DIST**2.0D0
     B1=FSAT*DIST**4.0D0
   8 FORMAT(/,T12,F5.2,6X,D25.16,6X,D25.16)
     WRITE (6,8) DIST,A,B1
     DISTC(N)=DIST
     AC(N)=A
     AD(N)=B1
  50 CONTINUE
C
C    COMPUTATION OF SATURATED ACTIVITY OF CADMIUM COVERED
C    FOILS AND THE PRODUCTS AS(CD)*R**2 AND AS(CD)*R**4
C
     DO60 N=1,15
     READ(5,5) POS,C1,X,Y,Z
   5 FORMAT(5F9.0)
     READ(5,7) W
   7 FORMAT(1F9.0)
     DIST=(POS-1.750)*0.254D01
     C1=W*3.0*C1/(1.0D0-C1*T)
     ASAT=D1*C1/((1.0D0-DEXP(-D1*X))*(DEXP(-D1*Y)-DEXP(-D1*
     Z)))
     SAT=ASAT
     AMEAN=C1/5.0
     SIGMA=AMEAN**0.5D0
     WRITE(6,3) DIST,SAT,AMEAN,SIGMA
   3 FORMAT(T6,F5.2,6X,D25.16,6X,D25.16,6X,D25.16)
     A=SAT*DIST**2.0D0
     B1=SAT*DIST**4.0D0
     WRITE(6,9) DIST,A,B1
   9 FORMAT(/,T12,F5.2,6X,D25.16,6X,D25.16)
     DISTA(N)=DIST
     AA(N)=A
     BB(N)=B1
C
     PLOTTING OF COMPUTED PRODUCTS VERSUS R
C
  60 CONTINUE
     READ (5,30) (ITITLE(I),I=1,12)
  30 FORMAT(6A8)
     CALL DRAW (15,DISTC,AC,0,3,LABEL2,ITITLE,0,0,0,0,0,0,6
     .9,1,LAST)
     READ (5,31) (ITITLE(I),I=1,12)
  31 FORMAT(6A8)
     CALL DRAW (15,DISTC,AD,0,3,LABEL2,ITITLE,0,0,0,0,0,0,6
     .9,1,LAST)
     READ (5,32) (ITITLE(I),I=1,12)
  32 FORMAT(6A8)
     CALL DRAW (15,DISTA,AA,0,4,LABEL3,ITITLE,0,0,0,0,0,0,6
     .9,1,LAST)
     READ (5,33) (ITITLE(I),I=1,12)
  33 FORMAT(6A8)
     CALL DRAW (15,DISTA,BB,0,5,LABEL4,ITITLE,0,0,0,0,0,0,6
     .9,1,LAST)
C
C    COMPUTATION/PLOTTING OF LOG AS*R**2 AND LOG AS(CD)R**2
C    VERSUS R AND COMPUTATION OF A LEAST SQUARE FIT OF
C    PLOTTED DATA.
C    NOTE: FOR THE PURPOSE OF LEAST SQUARE FIT ONLY DATA
C    POINTS FOUR THROUGH FIFTEEN ARE USED SINCE THIS IS
C    THE ONLY PART OF THE CURVE USED TO ESTIMATE THE
C    RELAXATION LENGTH

     DO70 N=1,15
```

```
   AC(N)=ALOG(AC(N))
   AA(N)=ALOG(AA(N))
70 CONTINUE
   READ (5,34) (ITITLE(I),I=1,12)
34 FORMAT(6A8)
   B(1)=0.0
   B(2)=0.0
   B(3)=0.0
   DO25 I=4,15
   B(1)=B(1)+AC(I)
   B(2)=B(2)+AC(I)*DISTC(I)
   B(3)=B(3)+AC(I)*DISTC(I)**2
25 CONTINUE
   DO26 L=1,4
   SUM(L)=0.0
26 CONTINUE
   DO 35 L=1,4
   DO 35 I=4,15
   SUM(L)=SUM(L)+DISTC(I)**(L)
35 CONTINUE
   C(1,1)=12
   DO45 M=1,3
   DO45 N=1,3
   IF(M+N.EQ.2) GO TO 45
   C(M,N)=SUM(M+N-2)
45 CONTINUE
   WRITE(6,55) B(1),B(2),B(3)
55 FORMAT(2X,'VALUES OF B',10X,3F15.4)
   WRITE(6,65)(SUM(L),L=1,4)
65 FORMAT(2X,'SUM OF XI',10X,4F15.4)
   WRITE(6,75)((C(M,N),M=1,3),N=1,3)
75 FORMAT(2X,'VALUES OF C',5X,9F12.4)
   CALL SIMQ(C,B,3,KS)
   WRITE(6,85) B(1),B(2),B(3)
85 FORMAT(2X,'SOLUTION',6X,3F10.4)
   U(1)=10.0
   DO 95 I=1,401
   V(I)=B(1)+U(I)*(B(2)+U(I)*B(3))
   U(I+1)=U(I)+0.05
95 CONTINUE
   CALL DRAW (15,DISTC,AC,1,3,LABEL2,ITITLE,0,0,0,0,0,0,9
   ,15,1,LAST)
   CALL DRAW(401,U,V,2,0,LABEL2,ITITLE,0,0,0,0,0,0,6,9,1,
   LAST)
   B(1)=0.0
   B(2)=0.0
   B(3)=0.0
   DO23 I=4,15
   B(1)=B(1)+AA(I)
   B(2)=B(2)+AA(I)*DISTA(I)
   B(3)=B(3)+AA(I)*DISTA(I)**2
23 CONTINUE
   DO27 L=1,4
   SUM(L)=0.0
27 CONTINUE
   DO36 L=1,4
   DO36 I=4,15
   SUM(L)=SUM(L)+DISTA(I)**(L)
36 CONTINUE
   C(1,1)=12
   DO46 M=1,3
   DO46 N=1,3
   IF(M+N.EQ.2) GO TO 46
   C(M,N)=SUM(M+N-2)
46 CONTINUE
   WRITE(6,56) B(1),B(2),B(3)
56 FORMAT(2X,'VZLUES OF B',10X,3F15.4)
   WRITE(6,66)(SUM(L),L=1,4)
66 FORMAT(2X,'SUM OF XI',10X,4F15.4)
   WRITE(6,76)((C(M,N),M=1,3),N=1,3)
76 FORMAT(2X,'VALUES OF C',5X,9F12.4)
   CALL SIMQ(C,B,3,KS)
```

```
      WRITE(6,86) B(1),B(2),B(3)
   86 FORMAT(2X,'SOLUTION',6X,3F10.4)
      U(1)=10.0
      DO96 I=1,401
      V(I)=B(1)+U(I)*(B(2)+U(I)*B(3))
      U(I+1)=U(I)+0.05
   96 CONTINUE
      CALL DRAW(401,U,V,2,0,LABEL3,ITITLE,0,0,0,0,0,0,6,9,1,
      LAST)
      CALL DRAW (15,DISTA,AA,3,4,LABEL3,ITITLE,0,0,0,0,0,0,6
      ,9,1,LAST)
      STOP
      END
```

```
C                       APPENDIX E
C
C
C
C        COMPUTER PROGRAM NO. 2
C
C
C
C        THE PURPOSE OF THIS PROGRAM IS TO COMPUTE DIFFUSION
C     LENGTH.  THE AREAS UNDER THE CURVED PORTIONS OF THE
C     CURVES AS*R**2,AS*R**4,AS(CD)*R**2 AND AS(CD)*R**4 ARE
C     COMPUTED BY SIMPSON'S RULE.  THE AREAS UNDER THE
C     LINEAR PORTIONS OF THE CURVES ARE COMPUTED BY THE
C    EQUATION Y=C2*EXP(-R/B).  THE TOTAL AREAS ARE USED TO
C     SOLVE FOR MIGRATION AREA AND AGE USING EQUATIONS (26)
C     AND (24).  DIFFUSION LENTH IS SOLVED BY
C     DL=(MIG-(AGE+1.8))**.5 WHERE THE 1.8 CORRECTION FACTOR
C     CORRECTS FOR ADDITIONAL AGE REQUIRED TO REACH THERMAL
C     ENERGIES.
C
C
C
C     PROGRAM NOTATION
C
C
C
C     B    RELAXATION LENGTH
C     BCD  RELAXATION LENGTH - CADMIUM COVERED FOILS
C     R    DISTANCE FROM SOURCE
C     S2   AREA UNDER AS*R**2 CURVE
C     SCD2 AREA UNDER AS(CD)*R**2 CURVE
C     S4   AREA UNDER AS*R**4 CURVE
C     SCD4 AREA UNDER AS(CD)*R**4 CURVE
C     MIG  MIGRATION AREA
C     AGE  AGE
C     DL   DIFFUSION LENGTH
      REAL*8 H,SUM2,SUM4,SCD2,S4, SCD4,A2,ACD2,AS2,AS4,ASCD2
     1S2,Y,YCD,C2,R
      DIMENSION Y(100),YCD(100),R(100)
C
C
C     RUN NUMBER SIX - CONC 8 GM/L - TEMP 131F
C
C
      READ(5,10) (Y(I),I=1,10)
   10 FORMAT(1F10.0)
      B=11.4
      C2=3000000.0
      READ(5,50) (YCD(I),I=1,10)
   50 FORMAT(1F10.0)
      BCD=9.0
      CD2=710000.0
C
C     COMPUTING SATURATED ACTIVITY TIMES DISTANCE SQUARED AR
C     AS*R**2
C
C
      DO160 I=11,80
      R(I)=1.0*(I)
      Y(I)=C2*DEXP(-R(I)/B)
      H=1.0
      N=79
      SUM2=0.0D0
      SUM4=0.0D0
      M=N-1
  160 CONTINUE
      DO20 I=3,N,2
      SUM2=SUM2+Y(I)
```

```
   20 CONTINUE
      DO30 I=2,M,2
      SUM4=SUM4+Y(I)
   30 CONTINUE
      S2=H/.3D1*(Y(I)+.4D1*SUM4+.2D1*SUM2+Y(N+1))
      WRITE(6,40) S2
   40 FORMAT(T19,'SIMPSONS APPROXIMATION',D25.16///)
C
C     AS(CD)*R**2
C
      DO230 I=11,80
      R(I)=1.0*(I)
      YCD(I)=CD2*DEXP(-R(I)/BCD)
      H=1.0
      N=79
      SUM2=0.0D0
      SUM4=0.0D0
      M=N-1
  230 CONTINUE
      DO60 I=3,N,2
      SUM2=SUM2+YCD(I)
   60 CONTINUE
      DO70 I=2,M,2
      SUM4=SUM4+YCD(I)
   70 CONTINUE
      SCD2=H/.3D1*(YCD(I)+.4D1*SUM4+.2D1*SUM2+YCD(N+1))
      WRITE(6,80) SCD2
   80 FORMAT(T19,'SIMPSONS APPROXIMATION',D25.16///)
C
C     COMPUTING SATURATED ACTIVITY DISTANCE TO THE FOURTH AR
C
C     AS*R**4
C
      DO90 I=1,10
      R(I)=1.0*(I)
      Y(I)=Y(I)*R(I)**2.0
   90 CONTINUE
      H=1.0
C
C       EXPODENTIAL PORTION
C
      DO 200 I=10,80
      R(I)=1.0*(I)
      Y(I)=C2*DEXP(-R(I)/B)*R(I)**2.0
  200 CONTINUE
      N=79
      SUM2=0.0D0
      SUM4=0.0D0
      M=N-1
      DO100 I=3,N,2
      SUM2=SUM2+Y(I)
  100 CONTINUE
      DO110 I=2,M,2
      SUM4=SUM4+Y(I)
  110 CONTINUE
      S4=H/.3D1*(Y(I)+.4D1*SUM4+.2D1*SUM2+Y(N+1))
      WRITE(6,120) S4
  120 FORMAT(T19,'SIMPSONS APPROXIMATION',D25.16///)
C
C     AS(CD)*R**4
C
      H=1.0
      N=15
      DO 130 I=1,10
      R(I)=1.0*(I)
      YCD(I)=YCD(I)*R(I)**2.0
  130 CONTINUE
C
C       EXPODENTIAL PORTION
C
      DO 260 I=10,80
      R(I)=1.0*(I)
```

```
      YCD(I)=CD2*DEXP(-R(I)/BCD)*R(I)**2.0
  260 CONTINUE
      N=79
      SUM2=0.0D0
      SUM4=0.0D0
      M=N-1
      DO140 I=3,N,2
      SUM2=SUM2+YCD(I)
  140 CONTINUE
      DO145 I=2,M,2
      SUM4=SUM4+YCD(I)
  145 CONTINUE
      SCD4=H/.3D1*(YCD(I)+.4D1*SUM4+.2D1*SUM2+YCD(N+1))
      WRITE(6,150) SCD4
  150 FORMAT(T19,'SIMPSONS APPROXIMATION',D25.16///)
C
C
C     COMPUTING DIFFUSION LENGTH
C
      AS2=S2
      AS4=S4
      ASCD2=SCD2
      ASCD4=SCD4
      MIG=AS4/(AS2*6.0)
      WRITE(6,290) MIG
  290 FORMAT(T19,'MIGRATION AREA=',D25.16///)
      AGE=ASCD4/(ASCD2*6.0)
      WRITE(6,300) AGE
  300 FORMAT(T19,'AGE=',D25.16///)
      DL=(MIG-(AGE+1.8))**.5
      WRITE(6,310) DL
  310 FORMAT(T19,'DIFFUSION LENGTH=',D25.16///)
      STOP
      END
```

```
C                        APPENDIX  F
C
C
C
C          COMPUTER PROGRAM NO. 3
C
C
C
C        THE PURPOSE OF THIS PROGRAM IS TO COMPUTE AND PLOT
C     A POLYNOMIAL APPROXIMATION OF 1/L**2 (K**2)  AS A
C     FUNCTION OF BORIC ACID CONCENTRATION AND TEMPERATURE.
C     THE BORIC ACID CONCENTRATION IS EXPRESSED AS THE
C     MACROSCOPIC ABSORPTION CROSS-SECTION OF BORON.  THE
C     TEMPERATURE DEPENDENCE FACTOR (TN/TO)**.5 IS BASED ON
C     A REFERENCE TEMPERATURE OF 22.3 DEGREES CENTIGRADE.
C     REFERENCE DATA AT THIS TEMPERATURE IS FROM REF. (2).
C
C
C
C     PROGAM NOTATION
C
C
C
C     EA   MACROSCOPIC ABSORPTIN CROSS-SECTION
C     DL   DIFFUSION LENGTH
C     TN   MODERATOR TEMPERATURE
C     TO   MODERATOR REFERENCE TEMPERATURE
C
C
C
      REAL DL,EA,B,C,U,V,SUM,TN,TO,A
      REAL LABEL2/4H    /
      DIMENSION DL(10),EA(10),B(4),SUM(4),U(402),V(401),C(4,
      4),A(4)
      REAL*8 ITITLE (12)
      READ(5,10) ((DL(I),EA(I)),I=1,10)
   10 FORMAT(2F9.0)
      READ(5,34) (ITITLE(I),I=1,12)
   34 FORMAT(6A8)
      B(1)=0.0
      B(2)=0.0
      B(3)=0.0
      B(4)=0.0
      DO25 I=1,10
      DL(I)=1.0/DL(I)
      B(2)=B(2)+DL(I)*EA(I)
      B(3)=B(3)+DL(I)*EA(I)**2
      B(4)=B(4)+DL(I)*EA(I)**3
   25 CONTINUE
      DO26 L=1,6
      SUM(L)=0.0
   26 CONTINUE
      DO30 L=1,6
      DO30 I=1,10
      SUM(L)=SUM(L)+EA(I)**(L)
   30 CONTINUE
      C(1,1)=10
      DO 40 M=1,4
      DO 40 N=1,4
      IF(M+N.EQ.2) GO TO 40
      C(M,N)=SUM(M+N-2)
   40 CONTINUE
      WRITE(6,50) B(1),B(2),B(3),B(4)
   50 FORMAT(2X,'VALUES OF B',10X,4F15.4)
      WRITE(6,60) (SUM(L),L=1,6)
   60 FORMAT(2X,'SUM OFXI',10X,6F15.4)
      WRITE(6,70)((C(M,N),M=1,4),N=1,4)
   70 FORMAT(2X,'VALUES OF C',16F12.4)
```

```
      CALL SIMQ(C,B,4,KS)
      WRITE(6,80) B(1),B(2),B(3),B(4)
 80   FORMAT(2X,'SOLUTION',6X,4F10.4)
      U(1)=.01
      DO 90 I=1,401
      V(I)=B(1)+U(I)*(B(2)+U(I)*B(3)+(U(I)**2)*B(4))
      U(I+1)=U(I)+.001
 90   CONTINUE
      CALL DRAW(10,EA,DL,1,3,LABEL2,ITITLE,0,0,0,0,0,0,6,9,1
     ,LAST)
      CALL DRAW(401,U,V,2,0,LABEL2,ITITLE,0,0,0,0,0,0,6,9,1,
     LAST)
      TN=308.0
      TO=296.15
      A(1)=B(1)
      A(2)=B(2)
      A(3)=B(3)
      A(4)=B(4)
      A(4)=((TO/TN)**.5)*A(4)*.8862
      A(3)=((TO/TN)**.5)*A(3)*.8862
      A(2)=((TO/TN)**.5)*A(2)*.8862
      A(1)=((TO/TN)**.5)*A(1)*.8862
      DO 91 I=1,401
      V(I)=A(1)+U(I)*(A(2)+U(I)*A(3)+(U(I)**2)*A(4))
      U(I+1)=U(I)+.001
 91   CONTINUE
      CALL DRAW(401,U,V,2,0,LABEL2,ITITLE,0,0,0,0,0,0,6,9,1,
     LAST)
      TN=328.0
      A(1)=B(1)
      A(2)=B(2)
      A(3)=B(3)
      A(4)=B(4)
      A(4)=((TO/TN)**.5)*A(4)*.8862
      A(3)=((TO/TN)**.5)*A(3)*.8862
      A(2)=((TO/TN)**.5)*A(2)*.8862
      A(1)=((TO/TN)**.5)*A(1)*.8862
      DO 92 I=1,401
      V(I)=A(1)+U(I)*(A(2)+U(I)*A(3)+(U(I)**2)*A(4))
      U(I+1)=U(1)+.001
 92   CONTINUE
      CALL DRAW(401,U,V,2,0,LABEL2,ITITLE,0,0,0,0,0,0,6,9,1,
     LAST)
      TN=338.0
      A(1)=B(1)
      A(2)=B(2)
      A(3)=B(3)
      A(4)=B(4)
      A(1)=((TO/TN)**.5)*A(1)*.8862
      A(2)=((TO/TN)**.5)*A(2)*.8862
      A(3)=((TO/TN)**.5)*A(3)*.8862
      A(4)=((TO/TN)**.5)*A(4)*.8862
      DO 93 I=1,401
      V(I)=A(1)+U(I)*(A(2)+U(I)*A(3)+(U(I)**2)*A(4))
      U(I+1)=U(I)+.001
 93   CONTINUE
      CALL DRAW(401,U,V,2,0,LABEL2,ITITLE,0,0,0,0,0,0,6,9,1,
     LAST)
      TN=343.0
      A(1)=B(1)
      A(2)=B(2)
      A(3)=B(3)
      A(4)=B(4)
      A(1)=((TO/TN)**.5)*A(1)*.8862
      A(2)=((TO/TN)**.5)*A(2)*.8862
      A(3)=((TO/TN)**.5)*A(3)*.8862
      A(4)=((TO/TN)**.5)*A(4)*.8862
      DO 94 I=1,401
      V(I)=A(1)+U(I)*(A(2)+U(I)*A(3)+(U(I)**2)*A(4))
      U(I+1)=U(I)+.001
 94   CONTINUE
      CALL DRAW(401,U,V,3,0,LABEL2,ITITLE,0,0,0,0,0,0,6,9,1,
```

```
LAST)
STOP
END
```

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13. ABSTRACT

The temperature dependence of diffusion length for PU-BE neutrons in distilled water poisoned with boric acid was studied using concentrations of 1.0, 8.0, 16.0, and 30.0 grams per liter. Runs at each concentration were made at temperatures of 95, 131, and 167°F. The trend of temperature dependence was clearly established. A theoretical temperature dependence of κ^2, where $\kappa=1/L$ is proposed using a Maxwellian distribution and found to be in good agreement with the data reported in reference [2].

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